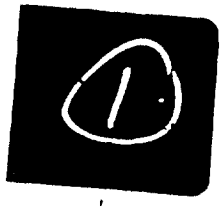

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The *Journal of Rehabilitation Research and Development*, published quarterly, is a scientific engineering publication in the multidisciplinary field of disability rehabilitation. General priority areas are: Prosthetics and Orthotics; Spinal Cord Injury and Related Neurological Disorders; Communication, Sensory and Cognitive Aids; and, Gerontology. The *Journal* receives submissions from sources within the United States and throughout the world.

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Editor's Note

Beginning with this issue, the *Notice to Contributors* printed on page ii, will inform authors that manuscripts are now required to be submitted in the "Vancouver" style. In the Vancouver style, now clearly and firmly established by the International Committee of Medical Journal Editors and published by the N Engl J Med 1991;324:424-8, as the generally accepted format for biomedical journals, references in the text are numbered consecutively in the order in which they appear and are identified by arabic numerals in parentheses. All papers published in the *Journal of Rehabilitation Research and Development* from the beginning of 1992 will be in the Vancouver format. All articles in this issue are referenced in the Vancouver style. Examples of this new format are listed in the *Notice to Contributors* on page ii.

A GUEST EDITORIAL

Desert Storm 1991: Orthopaedic Related Surgical Injuries

I have been asked by the editorial staff of the *Journal of Rehabilitation Research and Development* to provide some personal observations in my capacity as an orthopaedic surgeon assigned for five months to the 2nd General Hospital, Landstuhl Army Regional Medical Center (LARMC), Landstuhl, Germany during Desert Storm 1991. Prior to providing more factual information, my reflections include the honor of having the opportunity to serve the U.S. Army and the U.S. government as a member of the Armed Forces (Army). I am also appreciative that, as a member of the medical corps, our mission was to provide the highest caliber of medical/surgical care possible for our wounded or injured. A constant thought in my mind was the concern that those individuals who would ultimately enter the VA system of care would have received maximum care resulting in no impediment in their ultimate rehabilitation. My expectations were high that this goal could be accomplished—and was strived for constantly. I can honestly say that all the military medical colleagues with whom I had the good fortune to serve had the same motive, and were equally successful.

Col. Paul R. Meyer, Jr., M.D., F.S.

For the United States and its coalition forces, Desert Storm began during the nighttime hours of 17 January 1991. The initial thrust, until the initiation of the ground offensive on 24 February, was conducted by the air arms of the Army, the Air Force, and the Navy. Orthopaedic injuries prior to the initiation of the combined air/land operation consequently were primarily the result of military activities associated with the influx of a large number of troops stationed throughout Southwest Asia, in preparation for, or participation in, war activities. The primary causes of the initial casualties were accidental and enemy-related missile and mine injuries, along with a wide variety of other orthopaedic injuries resulting from living, driving, and participating in recreational activities within a desert environment.

Preparations for the potential orthopaedic aspects of war for both the active and reserve military medical officer begins long before the onset of any conflict. Actually, an orthopaedic surgeon trains for the management of war-incurred wounds during the performance of orthopaedic surgery in the course of daily surgical practice. Furthermore, the military surgeon maintains familiarization training for the potential of operating under conditions or settings foreign to his customary environment.

Beginning in early August of 1991, with the initiation of Operation Desert Shield, came the mobilization of large numbers of ground forces, along with medical personnel. First, they were assigned to units within the continental United States, then others were assigned to units within the European and Southwest Asia commands. This officer was assigned to the European theater.

Sixty-three U.S. Armed Services medical/surgical hospital units participated in Desert Storm. Of those, 44 were U.S. Army hospitals. The primary military general hospitals within Germany

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(Landstuhl, Frankfurt, Nuremberg) served as the principal evacuation receipt centers for injuries and war wounds exiting in Southwest Asia. The majority were evacuated to LARMC, Landstuhl, Germany, the site from which the following data are derived.

Between 17 January until 29 March, 7,500 evacuations from Southwest Asia occurred. Thirty-five percent (35%), or 2,679, were evacuated to LARMC. Of those, approximately 35% were orthopaedic-related injuries. Of the Desert Storm orthopaedic data collected, the most interesting observations have been the unbelievably small number of high velocity (rifle–17) weapon injuries and the sparsity of lower extremity amputations (13) resulting from exploding land mines. The low incidence of these two modes of injury were directly related to, and proportional to, the shortness of the ground war and the essential absence of hand-to-hand combat between adversarial forces.

As noted earlier, the majority of war-related causes of injury, following "soldiering activity" related to living and surviving within the semi-hostile desert environment. Examples included a large number of highway accidents resulting in both injury and/or deaths. The cause for this high incidence lies in the occurrence of traffic carrying both arms and personnel into the desert on either existing roadways or unimproved terrain. Other "soldiering-types" of injuries (52) resulted from working within the environment of heavy equipment, the occurrence of sports and after-dark injuries (i.e., falls into foxholes), or falls from structures being erected within the desert environment (14). Of war wounds incurred, the majority were of the crush injury type (34), gunshot wounds (17), land mine injuries (17), wounding secondary to SCUD missiles (15), etc. The remaining 95 of the 210 orthopaedic war-related injuries resulted from activities such as: anti-tank warfare, grenades, helicopter accidents, cluster bombs, mortar injuries, or "friendly fire."

War surgery, particularly orthopaedic war surgery, is an area of surgical medicine which has received careful scrutiny by military physicians since war surgery records were initiated. The first careful chronicling of war wound statistics was recorded in the War of the Crimea in the early 1800s, followed by a very accurate analysis by the Army Medical Department during and following the War of the Great Rebellion (Civil War), 1861-65. The mechanism of injury in most war wounds is the receipt of some form of high velocity injury to soft and/or hard tissue, leading to a loss of skin, muscle, or bone, resulting in a loss of all tissue vascularity, each within a highly contaminated environment. Thus, the most important surgical procedure that can be performed in all war wounds, including those that occurred in Desert Storm, is thorough and careful wound debridement, redebridement, and wound stabilization.

What may be looked upon as philosophically one of the more significant deviations in Desert Storm war wound management, from wound management techniques utilized during World War II, Korea, and Vietnam was the early use of hardware, both external and internal, in the management of open injuries. Noted with interest, reluctance, and suspicion (due to prior orthopaedic and military medical education) while serving in El Salvador (1985), was the early use of internal fracture stabilization in open war wounds. Now, with enhanced medical care and immediate patient evacuation to tertiary care facilities within hours of injury, followed by early wound debridement, stabilization, and appropriate antibiotics, these same management techniques were being utilized in the management of Desert Storm wounds. This method of management proved to be efficacious regardless of the magnitude of injury. The safe use of internal hardware following meticulous wound debridement and redebridement, along with the occasional abbreviated use of an external fixator, appropriate antibiotics, and early closure within 1-2 weeks (using vascularized muscle pedicle or free pedicle flaps and split thickness skin grafts), was demonstrated to be a most successful management scheme. Utilizing these techniques uniformly resulted in early soft tissue wound healing and provided for fracture stabilization which preserved heretofore unsalvageable extremity injuries.

Of the injured cared for at LARMC (444), there were 194 open fractures, 49 meniscal injuries, 47 closed fractures, 36 joint dislocations, 31 ligament ruptures, and a variety of other orthopaedic injuries. The most frequently performed orthopaedic surgical procedures included the following: wound debridement, application of external fixators, skin grafts, and delayed primary wound closures followed by the internal stabilization of long bone fractures.

Of those patients who sustained war-related traumatic extremity amputations (13), residual limb prosthetic concerns were always a consideration. To this end, there was careful adherence to the principle of maintaining optimal residual limb length and good tissue coverage. Open wound management with repeated debridement, the use of stockinette–Benzoin skin traction and the maintenance of maximum possible bone length continues to be the most successful means of managing this type of wound. It was generally noted that the amputation wound could be closed within 3 weeks, regardless of the mechanism of injury (land mine, crush, burn, etc.). Postoperatively, and prior to evacuation from the European theater, amputee wound management included the frequent reapplication of compressive extremity elastic dressings.

When asked, "What were the primary orthopaedic surgical lessons learned in this war (Desert Storm)?" the following might be said . . . that the United States provides an unexcelled opportunity for its wounded to receive the highest caliber of medical care available anywhere, within hours of the injury or wounding; that well-trained orthopaedic surgeons were mobilized and available at every level of the care process, including the desert, in Europe, and in the continental United States; that early patient resuscitation and initial wound debridement was immediately followed by evacuation to the European tertiary hospital for further medical or surgical tertiary care (within 6 to 32 hours of wounding). Such care resulted in an exceedingly high survival and recovery rate. The use of the external fixator in the stabilization of massive soft tissue injuries and long bone fractures provided an environment which allowed ease of patient transport, relief of pain, and enhanced wound care and recovery. Heretofore, the insertion of hardware in long bone injuries, incurred under wartime conditions, was a mechanism of wound management looked upon with a high degree of suspicion. What has been noted, however, was that good wound management, plus early skin coverage (to include muscle pedicle flaps) greatly enhanced soft tissue healing and vascular resupply to long bones, allowing for early and successful implantation of internal fracture fixation hardware. Each of the above provided an opportunity for rapid mobilization of the patients, a significant improvement in patient comfort throughout the care process, a more expeditious entry into the rehabilitation process of the Department of Veterans Affairs, and reentry into the mainstream of life.

Paul R. Meyer, Jr., M.D., F.S.
Professor of Orthopaedic Surgery
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Colonel, Medical Corps, U.S. Army Reserves
Orthopaedic Consultant (Reserves) to the Surgeon General, U.S. Army

LETTER TO THE EDITOR

Re: **Below-Knee Amputee Gait with Dynamic Elastic Response Prosthetic Feet: A Pilot Study**[1]

To the Editor:

The authors of the pilot study on dynamic elastic response feet are to be commended for the comprehensive and objective measurements reported. The Pathokinesiology Laboratory at Rancho Los Amigos is an ideal setting to investigate this area of conflicting subjective claims.

As the authors have anticipated in their discussion, however, readers with significant clinical experience fitting a variety of such feet will question the validity of deliberately choosing NOT to optimize the dynamic alignment for each successive foot type. Although the subjective nature of optimum alignment is widely acknowledged, it also can have a profound effect on the function of prosthetic feet.

Amputees will acclimate to a broad variety of misalignments over time and compensate by altering their gait mechanics. The recent amputee who arrives at clinic wearing higher heeled shoes is a classic illustration. The decision NOT to optimize alignment for each foot/subject combination—over a range of cadences—contradicts contemporary standards for prosthetic care and inadvertently confounds the result by potentially masking differences between foot mechanisms.

A good analogy might be exchanging automobile engines to determine their propulsive capabilities. Simply bolting in a replacement is not sufficient; each must be individually tuned with careful (but somewhat subjective) carburetor and ignition adjustments prior to dynamometer testing. I believe the pilot study protocol demonstrates that simply bolting a fancy foot on a pre-existing prosthesis is ineffective but this does not accurately reflect clinical practice.

The subjects' uniform lack of enthusiasm for the Flex-Foot is puzzling. At Duke, we always offer our Flex-Foot candidates an extended trial with at least one other dynamic response foot, providing the Flex-Foot only if the amputee prefers it to the less expensive alternative. In our experience, over 90 per cent of those patients who have been given the option choose the Flex-Foot.

However, as previously reported, we provide serial realignment of the prosthesis over several weeks or months until the amputee is fully acclimated to the greater range of motion and other response characteristics of the device.[2] We agree with Hittenberger and others that optimal alignment for dynamic response feet must always be individualized but typically results in somewhat greater plantar flexion or anterior placement than for less responsive alternatives.[3] Such alignment changes enhance the deflection of the more flexible anterior lever arm of the sophisticated feet and presumably affect performance. We also agree with Supan's group that if such changes are exaggerated, gait parameters can be adversely affected.[4]

Data reported in the pilot study tend to support the hypothesis that the Flex-Foot configuration may not have been optimally aligned. The finding that ". . . knee torque approached zero by the end of midstance (Flex-Foot)" suggests insufficient anterior resistance. The speculation that "because none of our subjects chose the Flex-Foot at the end of the study, perhaps this rapid progression of body weight during single-limb support was perceived as instability by the amputee and not as an optimal characteristic," lends further support to this contention.

The fact that every amputee rejected the SACH foot, given an alternative, agrees with our clinical experience at Duke. We have speculated that the SACH design (and its single axis alternative) may require more effort from the amputee (at least at the BK level) than the more responsive alternatives, particularly at higher cadences or on inclines.[5] The amputee preference for either Seattle or CCII designs coincides with our clinical experience as well.

The fact that both the Seattle Litefoot and CCII are significantly lighter than the SACH or STEN may also be a factor. Since we believe the optimal alignment for both Seattle and CCII is closer to traditional SACH alignment than will be the case with the Flex-Foot, their universal popularity in this study may also be related to the lack of dynamic alignment optimization previously discussed.

The authors' comment that their subjects tended to select the prosthesis offering the greatest velocity is an intriguing one. If documented in subsequent studies, this may offer a rational and low cost means to determine the optimal foot/alignment configuration. It is certainly well established that one of the chronic liabilities of lower limb amputation is the inability to sustain the same pace as the two-legged population despite prosthetic restoration.

The authors have provided an excellent model for the scientific investigation of prosthetic gait parameters. The clinical field remains eager for the assistance of research scientists in determining the optimal prosthetic configuration for each individual amputee. It is hoped that these constructive criticisms will help further our joint mission, and that subsequent studies will not omit the critical factor of individualized cadence-appropriate dynamic alignment for each amputee/component combination.

Sincerely,

John W. Michael, M.Ed., C.P.O.
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[1] Leslie Torburn, Jacquelin Perry, Edmond Ayyappa, Stewart L. Shanfield: Below Knee Amputee Gait with Dynamic Elastic Response Prosthetic Feet: A Pilot Study. *Journal of Rehabilitation Research and Development*, 27(4): 369-384, 1990.

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Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand

Patrick E. Patterson, PhD; Judd A. Katz, EdD
Iowa State University, Ames, IA 50011; Auburn University at Montgomery, Montgomery, AL 36117

Abstract—Providing accurate sensory information to the individual with a myoelectric limb is of great importance for improving device use in a wide variety of tasks. A number of feedback systems presently being investigated rely on either vibrotactile or electrotactile skin stimulation, which does not provide sensory patterns similar to those in a natural grasping hand. A prototype system was developed to enhance sensory information transfer by using a technique in which the feedback modality (pressure) was the same as the grasping pressure. The present study compared the developed system (pressure) with vibrotactile feedback, vision, and compounds of these three modes. It was found that the pressure-pressure concept reduced grasping pressure replication errors and error variability.

Key words: *electrotactile/vibrotactile skin stimulation, grasping pressure, limb prostheses, myoelectric hand, sensory feedback system.*

INTRODUCTION

Childress, referring to the state of the art in closed-loop control in upper limb prostheses stated:

> At the present time relatively few restorative techniques used in clinical practice have closed-loop controllers purposely designed within them. Loops are closed by the human operator through vision and incidental simulation (audition, socket pressure, harness, etc.), but not often through design intention (1).

Address all correspondence and requests for reprints to: Professor P.E. Patterson, Department of Industrial Engineering and the Biomedical Engineering Program, Iowa State University, Ames, IA 50011.

Differences of opinion regarding the Childress comments still exist. Solomonow, Lyman, and Freedy have commented that, in the research laboratory, "A great deal of progress has been made through the various ASAS's (artificial sensory augmentation systems) toward sensory recovery for the disabled; however, limitation in both quantity and quality of information transmission has become evident, and more complex stimulation techniques need to be sought" (2). Yet, Herberts and Körner have indicated that "development of a system for sensory feedback in hand prosthesis has not been as successful as that of modern prosthesis control systems" (3). The path leading from the research laboratory to actual use in clinical practice is still filled with obstacles.

When one reviews the literature in closed-loop feedback, much activity and diversity in both systems and philosophies regarding feedback design are obvious. Some researchers address logistical issues, miniaturization, power packages, and simplicity of support systems in their designs, while others address physiologically-compatible stimulation and correlated relationships between hand prostheses and stimulus generators in the design and construction of feedback systems.

The goals of the present study were to (*a*) consider the research activity that has occurred over the last 20 years; and, (*b*) design and evaluate a closed-loop upper limb system that was intended to provide the most reasonable stimulus feedback message to the body. The investigators viewed the solution to the feedback issue as a three-fold problem: 1) the feedback stimulus must be correlated to the activity of the hand, that is, feedback stimulation must vary directly with the grip force of the terminal appliance. (Childress

described how this concept was incorporated at a rudimentary level for a hand prosthesis patent in 1916 by Rosset using pneumatic transmission of pressure from finger pressure pads) (1); 2) the feedback stimulus should replicate or fit the same mode of stimulation as the natural limb (pressure sensitivity); and, 3) the design of a task would allow development of a precise evaluation methodology so that conclusions could be reached on the accuracy and feasibility of a number of feedback systems.

Although correlation and stimulus replication are found in the research literature, they have seldom been investigated together. Sueda and Tamura believed that a feedback sensory device was more important for a powered prosthesis than for a cable-controlled device (4). They mounted strain gauges at the base of a split hook that controlled the presentation of correlated vibratory stimulation to the user. Their rationale for increased feedback was to increase the control of an artificial arm by means of signals transmitted to the user. Using their system, they indicated that it was possible to determine the thickness of a grasped object with the eyes closed.

If vision cannot be used, correlated feedback via another source of stimulation is desirable. Scott used a correlated feedback stimulus related to the amount of pressure generated by an artificial hand (5), but the feedback stimulus selected was electrocutaneous, which does not fit the natural mode of pressure. Salisbury and Colman employed an interesting concept of correlation where a slippage indicator was attached to an artificial hand (6). The indicator sensed shear force and switched on a hand motor, which then applied more pressure on the object by closing the hand. The feedback loop was limited to the internal mechanical structure of the prosthesis and did not signal the subject. Beeker, During, and den Hertog used barium tetanite crystals in the thumb of a prosthetic hand that became pressure-sensitive during gripping, with the subject receiving electrocutaneous stimulation as feedback (7). The feedback appears to have been dichotomous rather than correlated. (The subject was informed that hand contact had been made, but not the magnitude of the pressure being exerted by the hand.) Shannon investigated electrical and vibrating feedback stimuli and concluded that vibration was more appropriate than electrical stimuli (8). He concluded that when upper levels of electrical stimulation are set or when two electrical stimuli receivers are activated, subjects describe the sensation as painful. Shannon's study indicates an attempt to search for a more appropriate stimulus. In 1979, Shannon integrated a correlated feedback stimulus as it is related to pinchforce in the hand, but the feedback stimulus was electrocutaneous (9).

Prior and Lyman used electrocutaneous stimulation that was correlated to the position of the hand (10). The authors presented an eight-task research program to include multiple degree of freedom feedback systems, providing the subject with information on grasp force along with hand and elbow positions for above-elbow amputees. Grip force and hand position were sensed by transducers mounted in the hands. (Pressure may have been determined by hand position rather than force on an object.) Prior and Lyman used an interesting block-grasping task to evaluate the discriminatory precision of the feedback stimulus (10).

Solomonow, Lyman, and Freedy (2) did extensive work on testing various ASAS. They presented a two-point discrimination system that could provide input for missing fingertip pressure, and elbow positions that could be used in an above-elbow prosthesis. The authors examined three variables: spatial (position of the electrode on different body sites or electrode interdistance); temporal (the relationship of the timing of one impulse to another); and frequency (a series of slower pulses in one electrode versus a series of faster pulses in the second electrode). Their work also provides a mapping procedure to determine efficient areas for feedback stimulus sites.

Schmidl used a micropotentiometer in the thumb joint of a prosthetic hand in which the output voltage was controlled by the position of the micropotentiometer. Schmidl said, "As the hand seizes an object, the output voltage increases in proportion to the pressure that the thumb exerts on the object" (11). The feedback was electrocutaneous stimulation proportional to position of the hand.

Almström, Anani, Herberts, and Körner investigated the problem of electrode containment in the prosthetic socket (12). They questioned whether the EMG pick-up electrodes would be hampered by the electrical activity of the feedback electrodes. If the pick-up electrodes are placed too close together, the problem of neurological or muscle crosstalk can interfere with the control of the prosthesis.

Childress defined three types of signal flow in a prosthesis that were of interest to the investigators: type A was visual and auditory; type B was proprioceptive; and, type C dealt with the technical aspects of the prosthesis (1). Phillips indicated that the primary modalities used by sensory feedback systems are those of vision, audition, and touch (13). The investigators hypothesized that in order to produce a useful and successful feedback stimulus, two basic conditions must be met: 1) the feedback stimulus must correlate with the pinchforce of the prosthesis; and, 2) the feedback signal must fit the stimulus mode of the missing limb. Thus, the ideal feedback mechanism would gener-

ate correlated pressure—pressure that is related to the pinchforce of the prosthetic hand.

The concept of matching the feedback stimulus of the missing limb comes from conclusions of a long series of psychological experimentation dating back to the 1920s. The early experimental psychological researchers, Pavlov and Hovland, gave support to the constructs of equivalence of associability: "The premise of equivalence places a special premium on the investigation of arbitrarily related, as opposed to naturally occurring, events" (14). The early stimulus researchers believed that conditional relationships or attachments could be made with any pair of stimuli as long as they showed a contiguous relationship for an extensive number of conditioning trials. The concept of equivalence of associability is the approach taken by many of the contemporary biomedical researchers investigating feedback systems in prosthetic limbs.

Thorndike (15) became aware that arbitrarily related stimuli did not develop the strong relationship or connection that related tasks and stimuli develop. He hypothesized that a satisfying state of affairs (feedback system) tends to arouse a confirming reaction, and that if feedback is too irrelevant, it does not arouse a confirming reaction. Thorndike called the confirming reaction to a proper stimulus, "belongingness," indicating the possibility that equivalence of associability was an incorrect concept. Garcia and Koelling, Lawika, and Seligman are contemporary psychological researchers who have expanded belongingness into the "stimulus fittingness principle" (16,17,18).

The concept of extended physiological taction (EPT) was investigated in the recent research of Meek, Jacobsen, and Goulding (19). They indicated their work was based in part on the force-to-force feedback concept demonstrated by the Rosset patent application (1), and conceptually related to Simpson's Extended Physiological Proprioception (20), which refers to the ability of the individuals to extend proprioception beyond their actual limbs. "The EPT method has a one-to-one or extended correspondence of sensation to stimulation . . . the user would exactly feel the object that is grasped." Meek, *et al.*, were in agreement with the authors of this investigation in their review of feedback stimulation and feedback loops presently in use. They indicated that while vibrotactile and electrotactile stimulation were the most often used feedback modes, neither provides a one-to-one physiologically-compatible stimulation of the human senses (19). In short, these feedback modes do not provide the same stimulation effect as does natural grasping.

Meek, *et al.*, share a parallel point of view to the psychological concepts of belongingness and stimulus fit previously discussed. Although the authors of this study share basic physiological and psychological issues, there are technological differences between the two approaches. They incorporated a strain gauge on the fingers of the terminal appliance. A circuit connected the strain gauge to a force applicator (a motor-driven pinion pushed a rack up and down against the skin of the remaining part of the arm). An extensive series of grasping tasks were then conducted to evaluate the effectiveness of the EPT system, resulting in what the authors felt was improved user performance (19).

The investigators in this research specifically used the stimulus fittingness principle in the theory and design of their feedback system for a myoelectric prosthetic hand. The feedback stimulus was correlated pressure (pressure in the cuff varied proportionally to pressure in the gripper) returned to the body via a pressure cuff. By incorporating the stimulus fittingness principle, the investigators hypothesized that learning precise use of a prosthetic hand could best be accomplished by providing a stimulus that matched that of the natural hand—the stimulus of pressure. When grasping an object, a subject does not expect noise, vibration, or electrostimulation; the subject expects the natural stimulus of pressure. The following procedure represents a comparison of feedback stimuli used by the investigators to evaluate their hypothesis.

METHOD

Apparatus

Figure 1 presents a block diagram of the experimental systems and the action sequence:

1. Control circuitry for the receipt and conditioning of EMG signals from the biceps and triceps. (The outputs of these two sets of electrodes were summed with the resulting differential indicating whether to increase [+] or reduce [−] grip pressure.)
2. A bidirectional motor that opened or closed a robotic hand in response to the EMG differential.
3. A Microbot MiniMover-5®, six-degree-of-freedom robotic arm, in which only the hand motor (number 2 above) was controlled in this study (all other degrees of freedom were fixed).
4. The pressure sensing circuitry on the gripper "fingers" consisting of a polyvinylidene fluoride piezoelectric film that generated a signal (pressure variations) which was translated into a corresponding voltage.
5. A single-board FORTH microcomputer for datalogging and transmission to the appropriate feedback device using the amplified voltage:

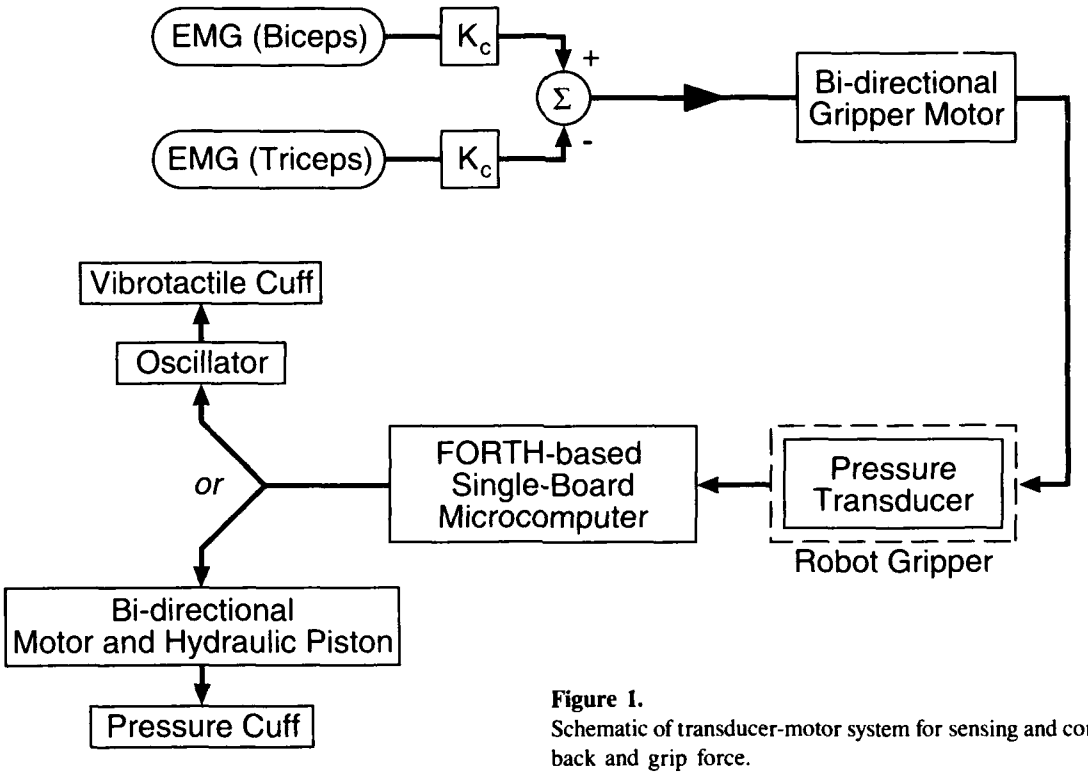

Figure 1.
Schematic of transducer-motor system for sensing and controlling feedback and grip force.

a. either to a pressure cuff (The polarity and magnitude of the signal drove a second bidirectional motor. The motor drove a small hydraulic piston that in turn exerted a hydraulic pressure in a pressure cuff around the upper arm.)

b. or to a vibrotactile cuff (The polarity and magnitude of the signal drove an oscillator for a miniature speaker imbedded in a cuff around the upper arm.)

Both cuff systems developed feedback responses that were proportional to the applied voltage.

Procedure

Twenty-five nonhandicapped university students, ages 18-25, were selected from a group of volunteers and randomly assigned to one of five feedback groups:

- Pressure only
- Vibration only
- Vision only
- Stimulus compound of pressure and vision
- Stimulus compound of vibration and vision.

Since both Childress and Phillips have indicated the value of vision (13,21), a multiple stimulus feedback condition was included in this study by adding and removing visual feedback from the stimuli of pressure and vibration.

The experimental area (**Figure 2**) consisted of a subject sitting at a 3 ft × 8 ft table that supported the equipment. Each subject sat at the end of the table and, depending on the assigned feedback group, was fitted with a stimulus cuff on the upper left arm that returned either the stimulus of vibration or pressure (subjects in the vision-only group did not wear a cuff). The table contained the control devices for vibration and pressure circuitry, a single-board computer, and a movable partition. By removing the partition, the vibration or pressure could be presented in a stimulus compound with vision by providing a view of the arm and gripper. Leaving the partition in place restricted the view of the arm and gripper, eliminated visual cues (i.e., deformation of the gripper fingers), and allowed vibration or pressure to be presented alone.

All subjects had the EMG circuitry affixed to their right arm for controlling the movement of the gripper hand on the end of the MiniMover robotic arm. The hand consisted of two industrial "fingers" that closed or pinched together when powered by an electric motor, giving the hand prehensile action. The closing velocity of the gripper was held constant, independent of the stimulus magnitude.

Pre-experimental trials

Each of the 25 subjects performed 50 familiarization trials within their assigned feedback mode. A wooden block

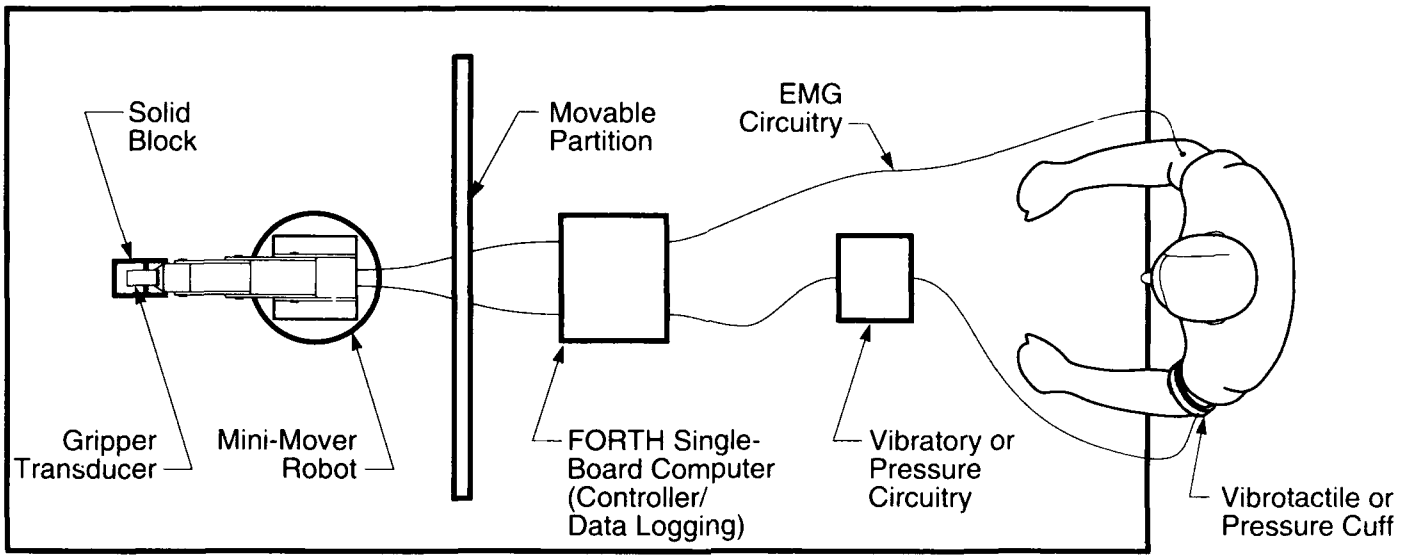

Figure 2.
Top view of the experimental area showing a subject in relation to the gripper hand and the solid block that the hand grasps. The illustrated subject is fitted with a cuff for vibration or pressure feedback with the movable partition in place to block vision of the gripper hand.

was placed between the fingers of the gripper hand and the subject was asked to grasp and squeeze the block by activating the EMG circuit. As the block was being squeezed by the robotic fingers, the investigator said, "Stop," logged the data value at that point in time on the FORTH microcomputer, and instructed the subject to relax. By using the stop command, the random pressure that was generated became the reference point for the replication trial. The experimenters' purpose for this procedure was to have the subject replicate a varying self-generated stimulus. This procedure also prevented the subject from simply maximizing the reference pressure and then generating the same maximum pressure during the replication (test) trial and thereby artificially inflating accuracy. In addition to the feedback condition of his assigned group, the subject received verbal knowledge of results as to the magnitude of pressure exerted by the gripper; the subject would then try to replicate that pressure. The pre-experimental trials allowed the subjects to practice opening and closing the gripper hand via the EMG transducer and to match their specific feedback system with a verbal report of the amount of pressure being exerted on the block.

Experimental trials

For the test, each subject performed 10 gripping trials on the same wooden block in the following sequence. No time restrictions were placed on the subject for responding; the bidirectional motor allowed for the correction of undershoot and overshoot in a response.

Reference trials

The reference and replication trials proceeded as in the pre-experimental trials with the exception of the presentation of verbal feedback. Subjects were not given verbal feedback as to the amount of pressure because they were in the pre-experimental trials but instead, received only the feedback stimulus specified by their assigned group (pressure, vibration, vision, pressure and vision, or vibration and vision). The subject then experienced an unfilled wait of 5 seconds before being asked to replicate the pressure.

Replication trial

After the 5-second waiting period, the subject was asked to match the pressure in the reference trial by activating the EMG system. The subject controlled the response by monitoring the feedback system provided to the assigned group. The subject said, "Match" to indicate when it was felt a match with the reference value was made; this point was marked by the investigator on the FORTH microprocessor.

A filled delay period of 30 seconds was inserted between each set of reference-replication trials; the filled delay consisted of a counting task. This was done to reduce any autocorrelation effect which might be present. Each subject was required to participate in 10 sets of reference-replication trials; error levels were recorded, indicating to what extent the subjects were able to duplicate their reference levels.

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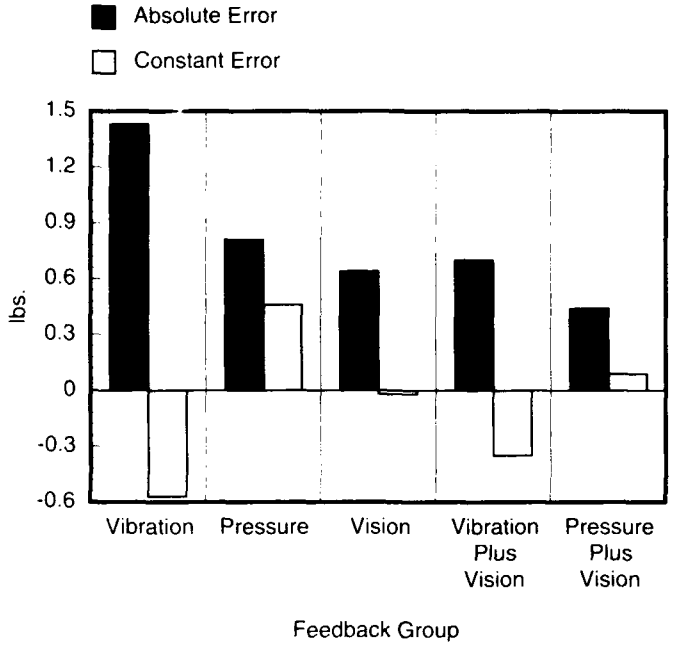

Figure 3.
The difference in absolute and constant error levels among the five groups.

RESULTS

Three different measures were used to interpret the results: 1) absolute error, defined as the magnitude of the error regardless of the sign, that is, overestimates (+) or underestimates (−); 2) constant error, defined as signed error (this indicates bias in the response, i.e., the tendency to overestimate or underestimate the response); and, 3) relative error, defined as the ratio of response error to the reference load—this measure allowed for comparisons between reference loads as these values were not fixed in this study (subject selected reference values).

Figure 3 shows the mean absolute and constant error values for each of the feedback modes. Note that the average response for the vision-only, vibration-plus-vision, and vibration-only conditions was typically an underestimate; that is, the replication trial value tended to be less than the reference value. In contrast, pressure-alone and pressure-plus-vision produced values that were biased in the overestimate direction; the replication value tended to be greater than that of the reference trial. In conjunction with these observations, the absolute error was greatest for the two supplemental feedback modes (pressure, vibration), while the presence of vision in a compound enhanced the accuracy of these same feedback stimuli.

Figure 4 depicts the effects of the feedback conditions on relative error. As was found with absolute error, the conditions of pressure-alone or vibration-alone gave the greatest error ratio per response. The three conditions involving vision had significantly lower relative error, with the pressure-plus-vision being lowest on this measure. Observe on this chart that while the vibration-plus-vision relative error was greater than that of the pressure-plus-vision condition and was approximately equal to the vision-alone condition, the vibration-plus-vision condition had the smallest response variability.

DISCUSSION

The results of this investigation tended to confirm the initial hypothesis that the mode of feedback stimulation generated by a grasping prosthetic hand should attempt to replicate the stimulation that one receives from the grip of a natural hand. The data support the findings of Meek *et al.*, as well as the observations of Childress and Phillips (13,19,21). Vision is a natural stimulus that enhances the effectiveness of a feedback stimulus and may derive from the fact that most of our motor tasks have become reliant on subtle visual cues. Levin and Haber, in their research on estimating distances, discovered that subjects were more accurate in judging radial distance (two inline objects in front of them) than in judging horizontal distance (two objects on the horizon in front of them) (22).

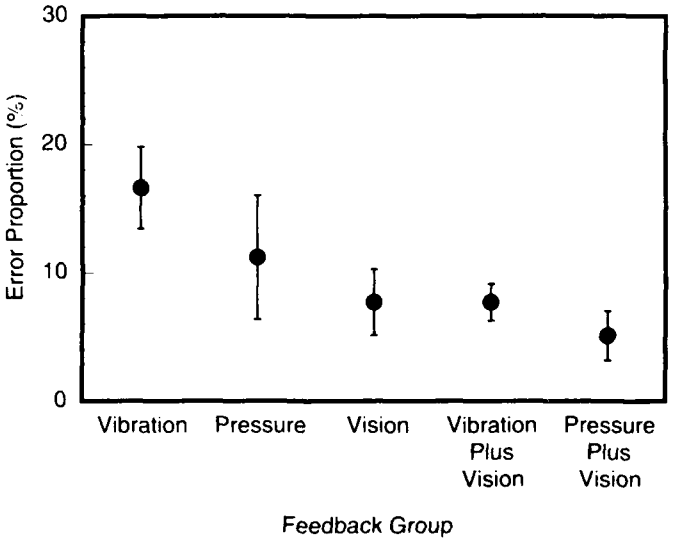

Figure 4.
Relative error: Error magnitude as a proportion of the reference trial (i.e., error/reference force).

Part of Levin and Haber's rationale for greater accuracy in judging radial distance was the change in visual texture of the ground when objects radiate outward. It is a subtle difference, yet is used in making more accurate distance discrimination. An analogy could be made for estimating pressure; additional visual cues from a gripping hand, even an artificial one, provide the subject with just enough information to make a more accurate tactile discrimination. Indeed, it appears that the primary advantage gained from supplemental feedback is that of reducing the variability of responses.

FUTURE DIRECTIONS

The results of the present study have implications not only for improving sensory feedback information to the user of a prosthesis, but also for systems involving the teleoperation of remote devices where such feedback would be beneficial. The results, while lending additional weight to the argument for using correlated feedback to enhance any sensory system relating pressure in a remote device, raise these additional questions which must be further addressed to assess the practical value of the technique:

- What effects might stimulus accommodation have on accuracy and long-term use? The present study used relative information, and so did not specifically address this issue.
- Which method would reduce learning time for first-time users; what is the effect of periods of nonuse on retention of accuracy?

and, perhaps the most critical questions of all,

- Can nonfitting or non-EPT feedback stimulation actually interfere with learning the precise use of a prosthesis?
- Is the information gained from receiving additional feedback worth the increase in device sophistication?

Additional research on these and related areas, coupled with philosophical and psychological discussions, are needed to answer these questions.

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Effect of functional bracing, quadriceps and hamstrings on anterior tibial translation in anterior cruciate ligament insufficiency: A preliminary study

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Abstract—Anterior tibial translation was measured in six patients with anterior cruciate ligament insufficiency. The tests were done in 15, 45, and 90 degrees of knee flexion, partly with activated quadriceps or hamstrings, and partly with subjects wearing a 4-point functional DonJoy brace. The translation was evaluated with a computerized electrogoniometer (Acufex KSS). The anterior tibial translation was significantly reduced by use of the hamstrings in all three degrees of knee flexion. The effect of the 4-point brace was only significant in 15 and 45 degrees of flexion. The quadriceps did not reduce the anterior tibial translation.

Key words: *Acufex KSS, anterior cruciate ligament insufficiency, anterior tibial translation, functional DonJoy brace, hamstrings, knee flexion, quadriceps.*

INTRODUCTION

The treatment of anterior cruciate ligament (ACL) insufficiency is still controversial (1,2,3), and many aspects concerning the biomechanics of the knee still need to be investigated (4). A major component in patients with ACL insufficiency is the anterior tibial translation (ATT) in relation to the femur. If conservative treatment is chosen, or if operative treatment is followed by early training, a functional brace can benefit the patient (5,6,7).

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The purpose of this study is to test the effect of the extensors and the flexors of the knee, as well as the effect of a functional brace, on the ATT in patients with ACL insufficiency.

METHOD

Six patients with unilateral ACL injuries were included in the study. (For patient characteristics see **Table 1**.) All patients had daily subjective complaints because of ACL insufficiency.

In order to measure the ATT, the ACL-insufficient knees were tested with an Acufex KSS laxity tester, using the contralateral knee as the control. Translation force was 100 N. The Acufex KSS (**Figure 1** and **Figure 2**) is a computerized electrogoniometer consisting of a test device mounted on the knee. Four potentiometers registered the anteroposterior tibial translation, knee flexion, tibial rotation, and varus/valgus displacement of the tibia in relation to the femur. The results were displayed on a computer monitor. With a special device connected to the computer, the anteroposterior translation force was applied to the tibia and also displayed on the monitor. The tests were done under standardized conditions because the same degree of knee flexion and the same applied force was repeated in each test. Each test was performed at least twice to be sure that the patient cooperated sufficiently. During each test, the patient sat on a test table with the leg clasped on a stand. Tests were done in three fixed degrees of knee flexion: 15,

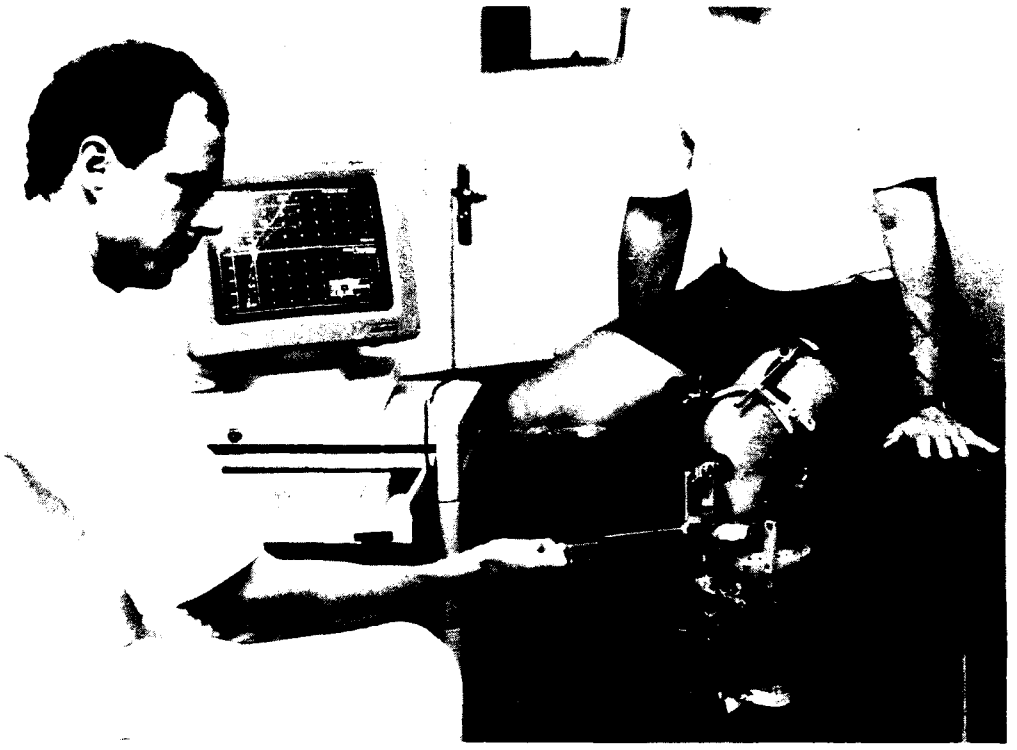

Figure 1.
The Acufex KSS: test setup.

45, and 90 degrees. Between each test, the patient rested for 1 to 2 minutes. Each test took 3 to 5 seconds.

The tests were done in four phases. During *Phase 1,* the ATT was measured on the relaxed knee, comparing the ACL-insufficient knee to the normal knee. The other phases tested only the ACL-insufficient knee. In *Phase 2,* the ATT was measured while the patients used their maximal hamstring force, and in *Phase 3,* they used maximal quadriceps force. In *Phase 4,* the ATT was measured on the relaxed knee with the knee braced with a 4-point functional brace (DonJoy-4-P).

The brace (**Figure 3**) consisted of two vertical aluminum alloy bars on each side of the knee, hinged by adjustable flexion-extension stops. Two aluminum alloy cuffs, an anterior thigh cuff, and a posterior calf cuff were fixed to the bars. The 4-point support was secured by two straps—a posterior thigh strap, and an anterior tibial strap; both were placed closer to the knee joint than the two cuffs. Before the trials, 180 measurements were completed on

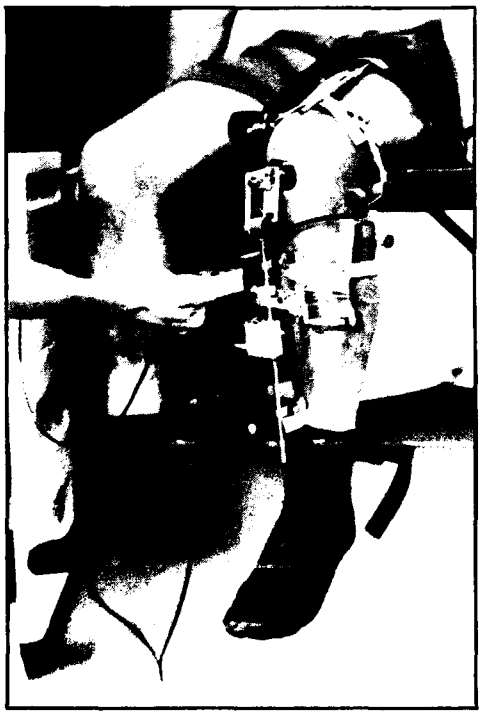

Figure 2.
The Acufex KSS: test device mounted on the knee.

Figure 3.
The functional brace: DonJoy-4-P.

Table 1.
Patient characteristics.

Patient No.	1	2	3	4	5	6
sex	F	M	F	M	M	M
age	30	38	29	25	27	32
diagnosis	arthrotomy	arthroscopy	arthroscopy	arthroscopy	arthroscopy	arthroscopy
treatment (ACL)	suture	none	none	none	none	none
other lesions	none	*	none	none	none	none
injury/study (time)	7 m	8 m	60 m	6 m	5 m	1 m

*Lesion of posterior horn of both menisci.
F = Female; M = Male; m = months.

6 normal knees to verify the accuracy of the test apparatus. If the test device was not removed from the knee during the tests, 92 percent of the tests were equal to, or differed from, the maximum of ± 1 mm from the median value. If the test device was removed from the knee between the tests, the accuracy was 78 percent ($p<0.05$).

As the leg was fixed in the test stand, varus/valgus displacement was zero, and in the tests of the ACL-insufficient knees, tibial rotation varied from zero to 13 degrees, with a median value of 1 degree. It was therefore assumed that the measurements of the tibial translation was not influenced by either varus/valgus displacement or tibial rotation in this setup.

RESULTS

Average ATT of the ACL-insufficient knee was compared with the nonaffected knee (see **Table 2**). The ATT was significantly demonstrated only in 15 degrees of knee flexion. A stabilizing effect on the ATT was obtained using the hamstrings (**Table 3**). The hamstrings significantly reduced the ATT as compared to the relaxed knee. The reduction, when the knee was fixed in 15 degrees of flexion, was 88 percent ($p<0.01$); 94 percent in 45 degrees of flexion ($p<0.025$); and 81 percent in 90 degrees of flexion ($p<0.01$).

In *Phase 3*, the measurements were done while the quadriceps was contracted and seemed to show a stabilizing effect on the ATT. But at the end of each test the patients relaxed their quadriceps, resulting in a backward gliding of the tibia. The sum of the measured reduction in ATT and the backward gliding was approximately equal to the primary measured ATT on the relaxed knee.

Table 3 shows that the 4-point brace significantly reduced the average ATT as compared to the relaxed knee in both 15 ($p<0.05$) and 45 ($p<0.025$) degrees of flexion, but not in 90 degrees of flexion ($p<0.25$). There was no statistical difference in the stabilizing effect when comparing the hamstring force to the brace.

DISCUSSION

This study was done with each patient sitting on a table with the knee fixed. The tibial rotation and varus/valgus displacement was negligible with this setup. Therefore, the results represent a static analysis of the stabilizing effect

Table 2.
Anterior tibial translation in relation to degrees of flexion for Affected and Non-affected knees.

ATT/Degrees of flexion	Average value (mm) Affected knee	Range	Average value (mm) Non-affected knee	Range	
15	7.8	(12.3 - 3.6)	3.3	(6.8 - 0.3)	$p<0.05$
45	6.0	(12.7 - 3.8)	5.3	(7.2 - 1.6)	$p<0.25$ NS
90	2.0	(4.2 - 0.5)	0.9	(2.2 - 0.0)	$p<0.4$ NS

Statistics were obtained by paired Student's *t*-test and the level of significance was 95 percent.

Table 3.
ATT in ACL-insufficient knees in 15, 45, and 90 degrees of flexion for relaxed knee, using hamstring force, and with brace.

Degrees of flexion	1	2	3	4	5	6	p value	Average decrease of ATT in percent
15	11.1	9.3	12.3	5.4	3.6	4.9		
15D	1.7	4.7	2.4	3.0	0.7	4.0	$p<0.05$	64
15H	2.4	0.8	0.1	0.5	0.9	0.7	$p<0.01$	88
45	12.7	8.7	5.3	5.8	3.8	5.6		
45D	0.4	1.9	1.7	0.7	1.6	0.9	$p<0.025$	82
45H	1.4	0.3	0.2	0.1	0.1	0.3	$p<0.025$	94
90	4.2	3.2	2.6	1.7	0.5	1.8		
90D	—	1.6	0.3	0.5	0.1	0.2	$p<0.25$	72
90H	0.1	0.1	0.1	0.2	—	2.0	$p<0.01$	81

D: with brace; H: use of maximum hamstring force.
Statistics were obtained by paired Student's *t*-test and the level of significance was 95 percent.

of knee extensors and flexors, as well as the effect of a 4-point functional brace. The reproducibility of the Acutex KSS electrogoniometer was acceptable. In the first phase of the study, the difference between ATT in the affected knee and the normal knee was clearly demonstrated in 15 degrees of flexion, replicating the clinical Lachmann test. When the patients used their maximal hamstring force, the ATT was significantly reduced, thus stabilizing the knee. The effect on the hamstrings was probably due to drawing the tibia backward while the posterior cruciate ligament acted as a counterstop, thereby stabilizing the knee (8). The quadriceps drew the tibia forward and at first had a stabilizing effect when maximally contracted. The lack of ACL led to a considerable sliding forward and backward of the tibia, resulting in a great load on the joint surface. Therefore, the quadriceps had no stabilizing effect on the ACL-insufficient knee. Conservative treatment for these patients should focus on hamstring exercises. The 4-point brace seemed to fixate the tibia in relation to the femur, avoiding inexpedient sliding of the tibia (9), but this needs to be further investigated in dynamic tests. As the healing time for reconstructed or augmented ACL may last up to one year (10), the use of a 4-point brace during active training might improve the long-term results for patients with ACL injuries.

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A Technical Note

A portable insole plantar pressure measurement system

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Abstract—To analyze plantar pressures during activities of daily living, one needs a fully portable system capable of measuring many steps over extended periods. This paper presents an inexpensive, reliable, portable plantar pressure acquisition system which we have developed. It allows the long-term recording (up to 2 hours) of pressure-time data from 14 pressure sensors within insoles. The sensor chosen is an inexpensive, conductive polymer sensor that is only 0.25 mm thick yet able to withstand sudden overloads. The portable, battery-powered, microprocessor-based data acquisition system has a memory space of 480 kbytes for data storage. It can collect pressure data from 14 insole sensors at a 20 Hz sample frequency for 5 seconds every minute over a 2-hour period. It enables the long-term measurement of plantar pressures during normal activities in a natural unrestricted environment. The design and development of this portable insole plantar pressure measurement system is described.

Key words: *activities of daily living (ADL), foot, gait, insole sensors, plantar pressure, portable data acquisition system.*

INTRODUCTION

There are many clinical situations where the measurement of forces exerted upon the plantar surface of the foot is of interest. Force plate studies generally represent barefoot, isolated steps and do not allow analysis of ongoing step-to-step variations in normal walking. These measurements may not be representative of the overall daily plantar pressures. The force plate system is limited to only one step or, at most, a few steps. Coupling information from both feet during walking is not easily obtained. It is not possible to measure pressure for a large number of steps under constant conditions. Thus, analysis of ongoing step-to-step variations in normal walking may not be possible.

Placing sensors within an insole provides a method for quantitation of plantar pressures during the normal activities of a shoe-wearing subject. This technique allows pressure quantification during the normal activities of a shoe-wearing subject. Discrete pressure sensors in the insole provide localized information; therefore, the site of the sensor placement is critical. Many of the available in-shoe pressure monitoring systems have thus far remained expensive with varying signal quality; many are dependent on an umbilical connection to a remote computer for data acquisition (**1–16**). They typically have a limited data acquisition period (20 seconds), and thus allow recording of only a few consecutive steps. Such an early foot-to-ground force measuring device with an instrumented shoe was reported by Spolek and Lippert in 1976 (1). The system was restricted to measuring heel and toe forces during several steps and was not portable. Miyazaki and Iwakura in 1978 presented a portable foot-force measuring system that used two pressure transducers under each foot (2). The Electrodynogram (EDG) (Langer Biomechanics Group, New York, NY), a commercial system, employs

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a microprocessor for acquiring in-shoe foot pressures from seven plantar locations (3,4). The EDG can acquire data for 5 seconds from the 14 channels but has been reported to lack repeatability and accuracy, with an inherent pressure variation as great as 100–200 percent (5). An umbilical system for measuring vertical reaction forces during gait was reported by Hermens *et al.*, in 1986 (6). The system used eight capacitive sensors which were attached to each sole. The system could store 16 kbytes of data for recording several consecutive steps during a 20-second period. Capacitive sensors (Hercules Aerospace Division, Cumberland, MD) have been used by Patel *et al.*, for measuring plantar pressures (17). The Hercules sensors are relatively expensive ($150 each), thick (2.4 mm), and fragile. The commercial EMED-System (NOVEL Electronics, Minneapolis, MN) also uses capacitive sensors for pressure measurement and is expensive ($6,000 per insole). A portable strain gauge dosimeter that quantifies foot-to-floor contact forces, and stores 256 kbytes of data from 6 sensors mounted within a single shoe was described by Harris *et al.*, in 1988 (7). Although completely portable, accurate, and reliable, the system was expensive and its use was limited to a restricted subject population. A recent commercial in-shoe pressure monitoring system, the F-Scan (Tekscan, Boston, MA) has been developed with 960 resistive sensors per insole. The insoles are usage-limited to a maximum of 50 cycles (steps) each. In addition, free unrestricted gait is not possible because the system utilizes an umbilical cable for data collection.

This paper describes an insole pressure measurement system that is reliable, cost-effective, and fully portable and allows the long-term recording (up to 2 hours) of pressure-time data from 14 pressure sensors within the insoles (18,19,20).

DESIGN CONCEPT

There are several components of the system that must be considered. The foot pressure sensor must not alter the natural gait of the subject. Therefore, it must be thin and flexible so that it will not be perceived by the subject. The sensor must be durable and capable of withstanding repetitive gait cycles, yet small and thin in order to fit in the insole. It should have high sensitivity, yet be able to withstand large overloads. It should have a short response time and low power consumption. The sensor must be wear-resistant, especially with friction or shear. Low hysteresis is highly desirable. Moderate nonlinearity is acceptable since the nonlinearity can be compensated for in the data processing software. The sensor should have a defined sensitivity to temperature and humidity so it can be compensated. It should be able to measure pressures in the range of 0 to 1.2 megapascals (MPa) with high stability and repeatability. The lead wire connections to the sensors should maintain electrical integrity while providing flexibility and durability.

The data acquisition system should be portable so that the gait being studied is not restricted to a small area around a host processor. The portable unit must have sufficient memory to store the complete pressure-time data at multiple sites with a high enough sampling rate to assure resolution of the complete signal. It should also have the ability to readily adjust the sampling rate required for different clinical tests. The system should be able to run for several hours without a battery change and be conveniently reprogrammed.

DEVICE DESIGN

Sensor evaluation

A large number of pressure sensors were screened (**17–24**). The requirement that the sensors be small and thin, in order to fit in the insole, eliminated most commercial sensors from consideration. Also, most commercial pressure sensors can withstand overloads of only 100 percent before failure due to permanent deformation. Thus, although pressures are measured in the normal range of 0–1.2 MPa, sensors are required that can withstand the occasional high pressures caused by jumping or stepping on a small object (e.g., a pebble under the shoe). With these requirements, the evaluations eliminated many commercial sensors, particularly those that use strain gauges.

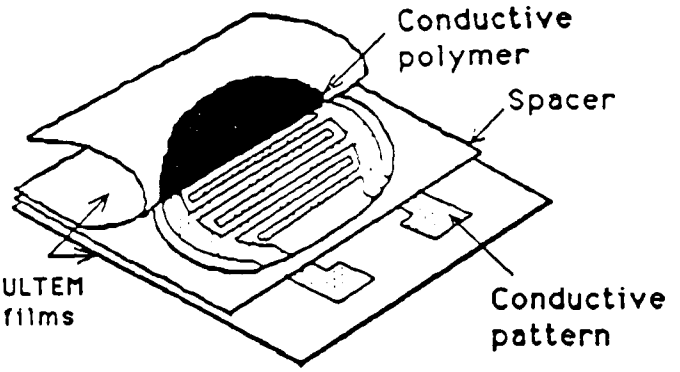


Figure 1.
Interlink pressure sensor 11 mm in diameter consisting of two layers: a conductive polymer film and a mylar layer impregnated with two interdigitated silver patterns.

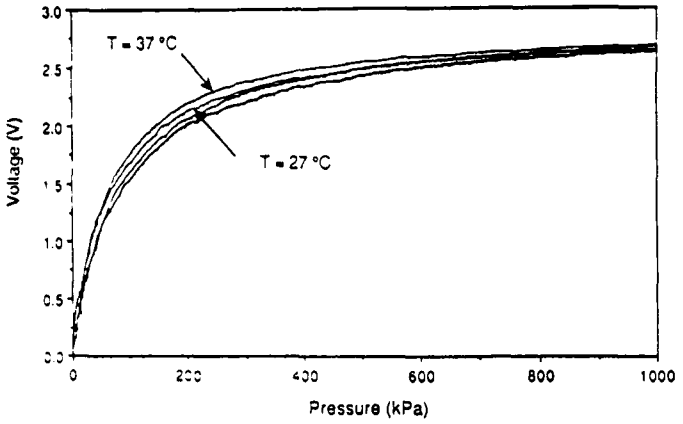


Figure 2.
Voltage-pressure response of an Interlink pressure sensor at two different temperatures. The sensor is more sensitive at low pressures and less sensitive at high pressures.

The initial sensor chosen was the Interlink 15-mm circle conductive polymer pressure sensor (18). This sensor (Interlink Electronics, Santa Barbara, CA) consists of two layers, a conductive polymer film suspended on a mylar film, and a mylar layer impregnated with two interdigitated silver conductive patterns. Observation of the bottom layer (using an electron microscope), reveals a surface with microscopic bumps, which act as parallel resistive switches that turn on at varying pressures. When the film is pressed against the conductive pattern, more and more bumps come in contact and cause the resistance to decrease. In the absence of pressure, resistance of the sensor is typically 10 MΩ. It is 0.25 mm thick, light, flexible, and costs about one dollar. The hysteresis is 8 percent and the nonrepeatability is less than 7 percent of full scale (0–1.2 MPa). The temperature drift is −0.5 percent/degrees C of full scale.

In May 1988, Interlink replaced the mylar construction with GE Ultem plastic, incorporated an O-ring spacer between the metal lands and the conductive polymer (**Figure 1**). These sensors are 11 mm in diameter and 0.5 mm in thickness. The resistance versus pressure characteristic of the sensor is logarithmic. Ten sensors were tested and it was found that the hysteresis was between 5 and 10 percent of full pressure scale of 0 to 1.2 MPa (19). The maximal pressure nonrepeatability for increasing pressure at any data point was between 5 and 8 percent of full scale. The rise time of the sensor was determined by measuring the time between 10 percent and 90 percent of maximal output response to a hammer strike and was about 0.26 ms during the rising and falling edges of the step response.

Figure 2 shows the characteristic of an Interlink pressure sensor. The sensitivity of the sensor with amplifier is nonlinear and ranges from 0.3 to 30 mV/kPa. It is more sensitive at low pressures and less sensitive at high pressures. The nonlinearity of the sensor was compensated by using a calibration lookup table. The maximal temperature related drift is −0.8 percent/degrees C. Since the sensor is sealed, it is insensitive to humidity. Advantages of these sensors are that they can withstand large overloads, are inexpensive, and need relatively simple circuitry. Disadvantages (nonlinearity, moderate hysteresis, and moderate temperature sensitivity) were compensated by the experimental protocol and use of calibration lookup tables.

Sensor placement

To determine where to place the sensors, many available footprint techniques such as APEX foot imprinter (APEX, Hackensack, NJ), microcapsule socks, Fuji Pressensor Mat, and Shutrack system for locating sensors were investigated. The APEX foot imprinter worked best for applications in terms of accuracy, simplicity, and cost. To determine the sites of greatest weight-loading, a subject walks three times on an APEX footprint mat that has been evenly inked and covered with paper. The operator averages the locations of the highest pressure area centers, which appear dark. The operator then aligns the APEX paper on the insole to lay out the seven sensor locations (20). **Figure 3** shows an instrumented insole with seven sensors and the connecting cable.

To reduce excessive hysteresis due to bending, small 1-mm thick metal backings were made for each sensor to keep them flat throughout the step cycle. The insole was hollowed out enough to accept the thickness of the metal backing, hence the resulting sensor was flush with the top surface of the insole. Subjects could not perceive the presence of the sensors in the insole while walking. Temperature distributions within the shoe were measured; there was a 30-minute stabilization period while the foot warmed up the shoe. Following the stabilization period, the temperature was nearly uniform within the shoe, at close to body temperature.

Sensor calibration

To compensate for the nonlinearity of the sensor, a sensor calibrator was constructed using a 440-N strain gauge load cell and amplifier (21). Forces were applied through a lever system with pin joints. To prevent force measured by the load cell from being transmitted through the O-ring spacer of the Interlink sensor, an 11-mm diameter spacer was cut and taped into position so that all forces

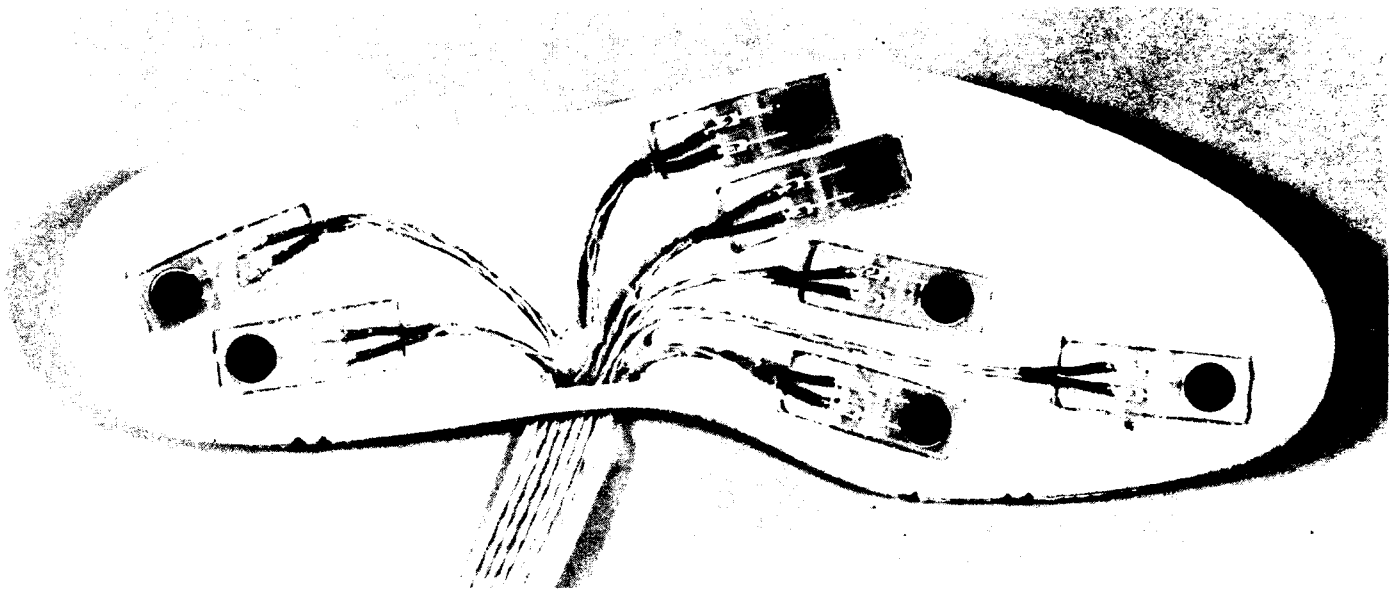


Figure 3.
An instrumented insole with seven pressure sensors located under the anterior and posterior heel, first metatarsal, second metatarsal, fourth metatarsal, fifth metatarsal, and great toe.

were transmitted through the active conductive polymer area of the sensor. Because the sensors are temperature-sensitive, an oven was constructed to surround the calibration apparatus and calibrated the insole sensors at 36 degrees C. The IBM PC-based data acquisition system samples the outputs from the sensor and load cell and stores a piecewise linear lookup table for use in compensation for the nonlinearity of the sensor.

Portable data acquisition system

The portable microprocessor-based data acquisition system can support the long-term (up to 2 hours) recording of pressure-time data from 14 sensors. As shown in **Figure 4**, the system consists of 14 conductive polymer pressure sensors, 14 amplifiers (LM358), an 8-bit analog to digital converter with on-chip 16-channel multiplexer (ADC0816), a microprocessor (Hitachi HD64180), an 8-kbyte CMOS ROM (Intel 27C64), 15 32-kbyte CMOS RAMs (NEC μPD43256), and interfacing I/O circuits (20). The insole data acquisition system is portable, battery-supplied, and book-sized. It consumes 19 mW at a clock frequency of 6 MHz by providing a SLEEP mode and a SYSTEM STOP mode. The system design permits adjustment of the sample rate (by hardware switch) up to 100 samples per second to study higher frequency pressures (utilizing the same software) such as those during running or jumping activities. This system can collect pressure data from 14 channels at a 20-Hz sample frequency for 5 sec-

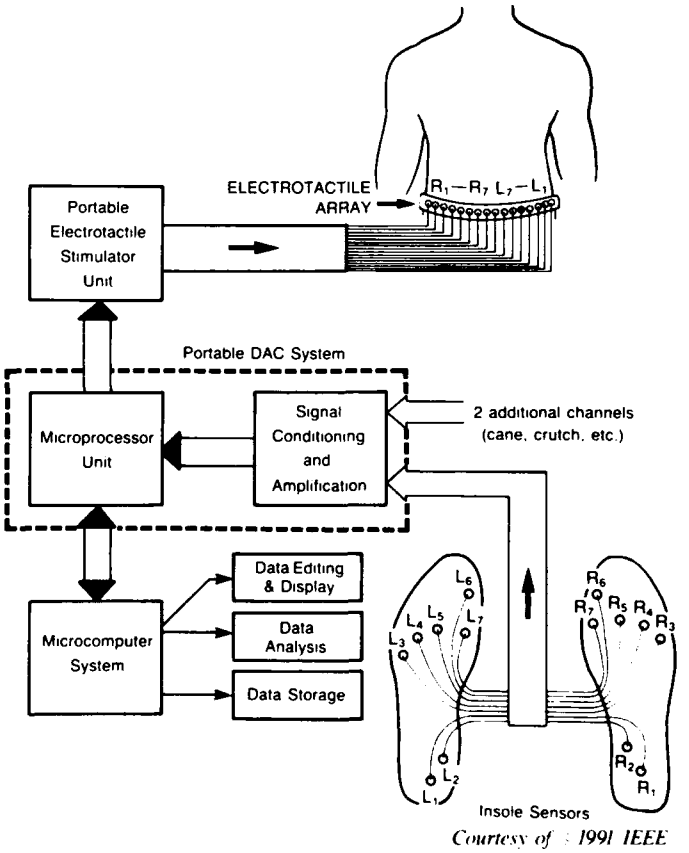
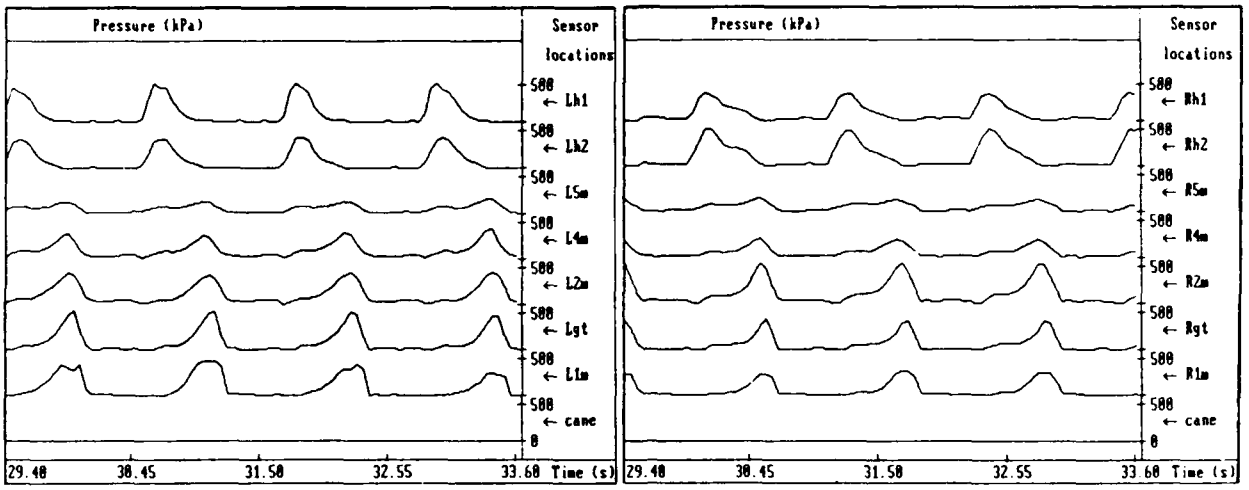


Figure 4.
Block diagram of the pressure data acquisition system, consisting of a pair of insoles instrumented with 14 pressure sensors, a portable microprocessor-based data acquisition system, and a microcomputer



Courtesy of Archives of Physical Medicine and Rehabilitation

Figure 5.
Foot pressures during normal walking as a function of time in a typical subject. From the top to the bottom, the curves represent plantar pressures under posterior heel, anterior heel, fifth metatarsal, fourth metatarsal, second metatarsal, hallux, and first metatarsal of each foot during consecutive steps. A scale of 500 kPa was indicated for each channel. (Reprinted, by permission, from Hongsheng Zhu, et al., Foot Pressure Distribution During Walking and Shuffling. Archives of Physical Medicine and Rehabilitation, 391, 72(6):390-397, 1991.)

onds every minute over a 2-hour period. It can also continuously collect pressure data for 15 minutes. The data acquisition unit is 20 × 18 × 7 cm in size and weighs 0.8 kg. Subjects carry it in a backpack during ambulation. After the test, the data are downloaded to the IBM PC, which translates the voltages into pressures by looking up prestored calibration tables. The system has the ability to run for 8 hours without a battery change and can be conveniently reprogrammed. **Figure 5** shows pressure-time data of a typical subject during normal walking.

CONCLUSION

A fully portable, microprocessor-based insole pressure measurement system is described. The system can be used to collect data for up to 2 hours. It is portable and does not interfere with the natural gait pattern of the subject. It allows analysis of plantar pressure-time data during activities of daily living in an unrestricted environment. The portable system has been used for studying sensate and insensate plantar pressures, shuffling gait versus normal walking, and loading pattern during contra/ipsilateral cane use (26,27,28). It has also been used to study cane cadence measurement, plantar pressures of total contact cast, and stump pressures of the below-knee prosthesis (unpublished observations). The system has been interfaced with a portable electrotactile stimulator to provide sensory feedback for the insensate foot (29).

Figure 4 *(Continued)*
for data display, analysis, and storage. An optimal electrotactile display is available. (Reprinted, by permission, from Hongsheng Zhu, et al., A Microprocessor-Based Data-Acquisition System for Measuring Plantar Pressures from Ambulatory Subjects. IEEE Transactions on Biomedical Engineering, 713, 38(7):710-714, 1991.)

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Toward a practical mobile robotic aid system for people with severe physical disabilities

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Abstract—A simple, relatively inexpensive robotic system that can aid severely disabled persons by providing pick-and-place manipulative abilities to augment the functions of human or trained animal assistants is under development at Rice University and the Baylor College of Medicine. A stand-alone software application program runs on a Macintosh personal computer and provides the user with a selection of interactive windows for commanding the mobile robot via cursor action. A HERO 2000 robot has been modified such that its workspace extends from the floor to tabletop heights, and the robot is interfaced to a Macintosh SE via a wireless communications link for untethered operation. Integrated into the system are hardware and software which allow the user to control household appliances in addition to the robot. A separate Machine Control Interface device converts breath action and head or other three-dimensional motion inputs into cursor signals. Preliminary in-home and laboratory testing has demonstrated the utility of the system to perform useful navigational and manipulative tasks.

Key words: *control panel; kinematics, manipulative aid, mobile robot, model-reflective command generation, personal autonomy, teleoperator, severely disabled, world modeling.*

INTRODUCTION

Robotic technology is being used to provide severely physically disabled people with increased independence in home and office environments (1–6). In addition to the personal benefits of increased autonomy, possible economic benefits underlie the application of robotics in the health care industry (7). Researchers at Stanford University/VA Medical Center (VAMC), Palo Alto, CA, Carnegie Mellon University, and Boeing Aerospace have developed robotic aid prototypes in the form of voice-activated workstations, in which personal items, work materials, and appliances are placed within reach of a fixed robot that can transport objects from one place to another or present objects to the user. Also, researchers at Stanford/Palo Alto VAMC developed a prototype voice-activated mobile robotic aid (8,9). PRAB Command Inc. commercialized (unsuccessfully) a robotic workstation based on the system developed at Boeing.*

Widespread application of robotic technology in rehabilitation is hampered by the high cost and limited utility of the equipment, lack of reliability, frequency and technicality of maintenance, and difficulty in training people to use a particular system. The prototype robotic system under development at Rice/Baylor addresses these issues. Costs are reduced by using off-the-shelf technology wherever possible. Aside from the Machine Control Interface (MCI), a framework for a useful system was developed using a modified HERO 2000 robot, a Macintosh SE host computer, and the X-10 Powerhouse household appliance controller (cost under $8,000). Utility of the system is enhanced by using equipment that is multifunctional. The MCI is designed to serve as an all-in-one control unit, capable of generating control signals for a variety of machines, including wheelchairs, a musical synthesizer, and personal

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*PRAB Command, Inc.: Voice Controlled Personal Robot, news release, Kalamazoo, MI, June 1988.

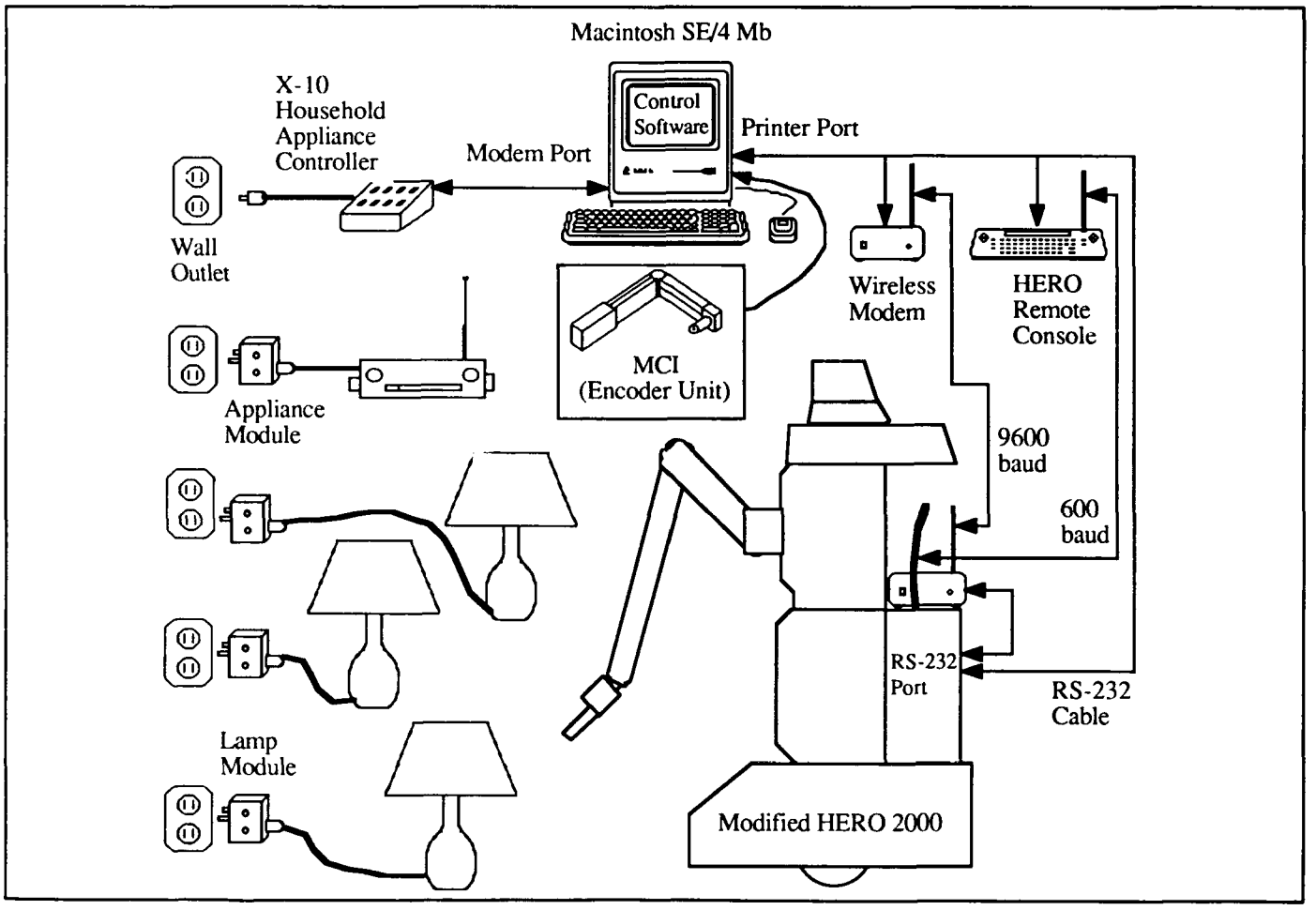

Figure 1.
Schematic of robotic aid system.

computers; thus, in the absence of the robot, the system can still serve as an environmental control unit and as a wheelchair controller. Increased hardware utility, reliability, and maintainability of the robot and its communication link have been the subject of ongoing efforts at Rice (10,11,12), but will continue to be the bane of the system until better technology and support are available from manufacturers. In the meantime, many of the hardware reliability problems have been ameliorated with more robust software. Moreover, the host computer and the robot itself have intrinsic value as personal computers, and are members of two very popular brands for which a great deal of software exists. The difficulty in training users has been addressed by keeping the human/machine interface simple. Many of the elements of the Macintosh user interface, including windows, control panels, and interactive graphics, are incorporated into the robot control software, which is entirely cursor-driven. The software exists as a stand-alone application on a single high-density 3.5 inch floppy disk. The entire system boots with the signal of a single click of a mouse.

METHODS AND MATERIALS

System configuration

Figure 1 is a schematic of the robotic aid system, in which a Macintosh SE, a HERO 2000 robot, and a Powerhouse X-10 household appliance controller are integrated. The host computer forms the hub of the system, communicating with the robot and appliance controller via its programmable baud rate serial printer and modem ports. At the expense of hindering the mobility of the robot, a cable presently provides the most reliable communications link between the host and the robot. The remote console (RC) supplied with the robot allows untethered operation

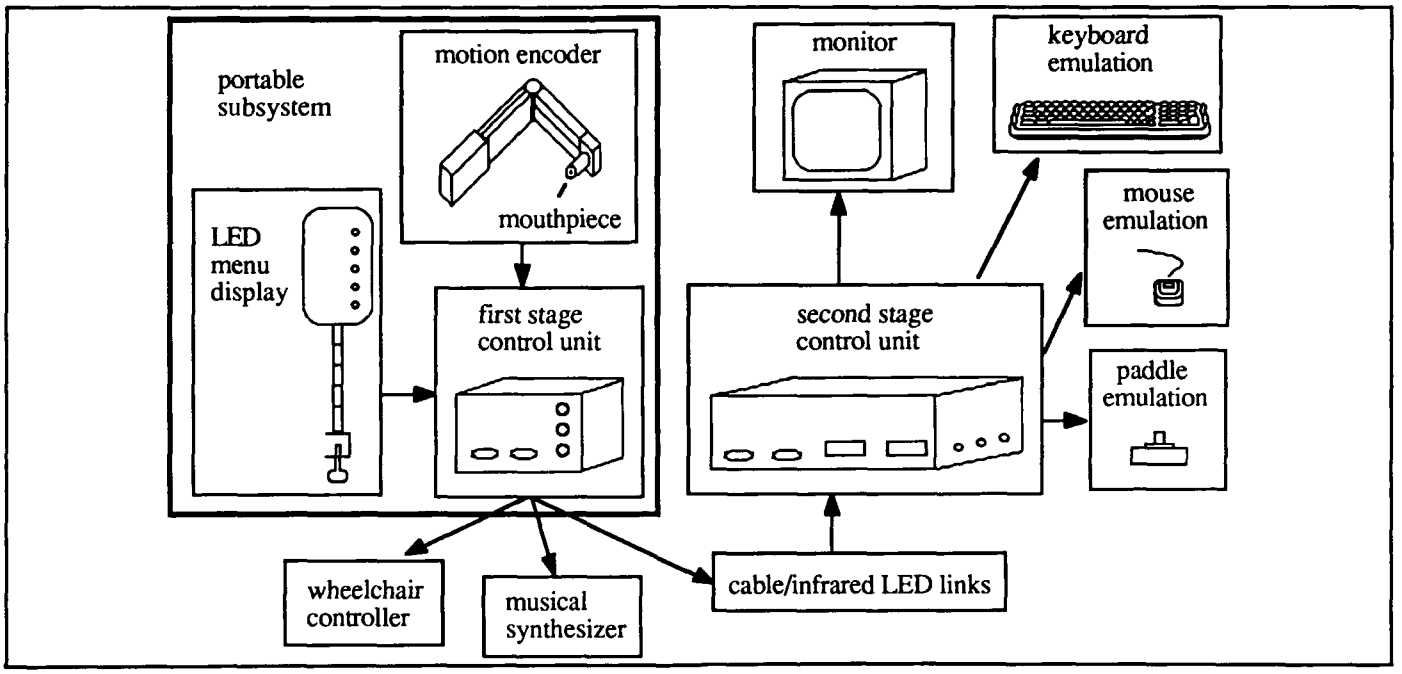

Figure 2.
Schematic of Machine Control Interface.

with a range of up to 50 feet, but at 600 baud the communications link is slow and can hamper the utility of the robot. The lack of dependable hardware handshaking in the RC requires extensive software error checking by communications routines on the host computer. The range and communications limitations of the console can be overcome at additional cost (several thousand dollars) by using a pair of 9600 baud wireless modems. These modems have been used with this project and several other projects where they proved to be reliable and able to solve the problems inherent with the HERO RC.

Robot

Designed for domestic and educational use, the HERO has a number of features which make it suitable for use as a domestic aid. With its 5-degree-of-freedom arm and parallel jaw gripper, the robot can manipulate payloads of up to 1 pound. Dual independent drive wheels in the base give the robot the ability to move forward and backward as well as to turn in place. An onboard 8088 microprocessor and independent motor controller processors simplify the task of programming the robot in BASIC. Arm joints are commanded directly in degrees and base movement in inches. MS-DOS can be run using an optional disk drive, hence languages other than BASIC can be supported.

Several mechanical components of the off-the-shelf robot have been modified to increase its utility. The original robot was able to reach from ground level to barely above 30 inches from the ground. By lengthening the second segment of the arm from 9 to 18 inches and raising the arm 9 inches in an extended torso section, the robot is able to reach above a tabletop height of 30 inches, with a 24-inch depth of reach at that height (10). A shock-absorbing suspension has been designed to replace the fixed suspension of the original robot (11). This modification alleviates problems with jerkiness in stopping, starting, and traversing small obstacles. A 3-degree-of-freedom wrist and a gripper with improved payload, dexterity, and sensing are currently under development (12).

Autonomous function of a robot depends on the ability of the robot to sense both its external environment and its internal state. The HERO is equipped with a suite of sensors for infrared light and sound detection, sonar range finding, temperature sensing, and low-battery sensing. The sonar and light sensors have been used in navigation routines involving obstacle avoidance, wall following, homing, and triangulation of position. By using an optional experimenter card it is reasonable to add even more sensors. For example, sonar and optical switch sensors have been designed for attachment to the robot gripper, and automated grasping routines have been implemented (13). In combination with the low-battery sensor, an infrared light detector is used in a routine for making the robot move to its charger. A speech synthesis unit, useful in providing audible feed-

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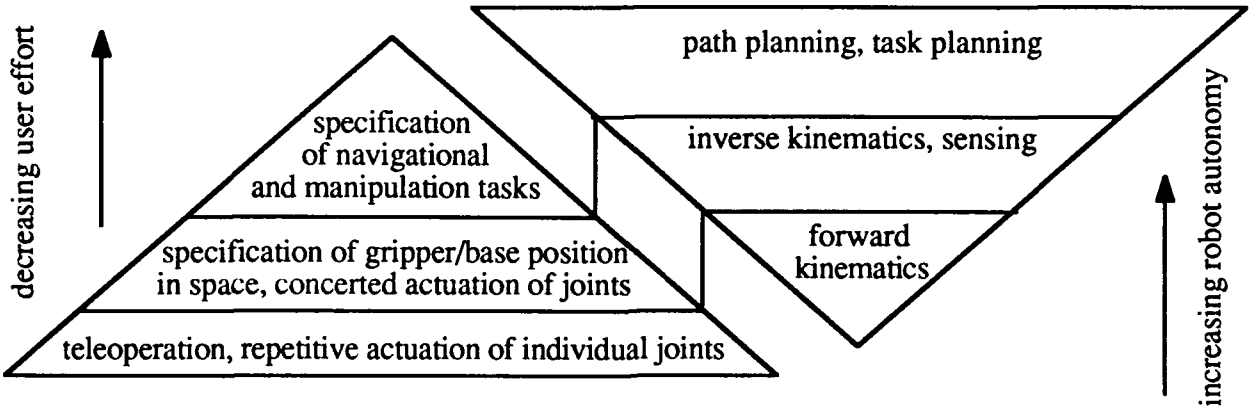

Figure 3.
Robot command hierarchy.

back to indicate that the robot has received commands, is among the various other features of the robot.

Machine control interface

The machine control interface (MCI) is a user-programmable unit that enables interaction with a wide range of electromechanical devices using one set of user-selected control inputs. The MCI is composed of a position encoder unit, a light-emitting diode (LED) menu display, and first- and second-stage control units (**Figure 2**). The position encoder, LED display, and first-stage control unit constitute a portable subsystem designed to be carried on the wheelchair of a user. The first-stage control unit has outputs for controlling a wheelchair and a musical synthesizer, or creating RS-232 encoded signals for controlling a computer. Using the RS-232 protocol, the first-stage control unit communicates with the second-stage over either cable or infrared links. The second-stage unit produces mouse, paddles, and keyboard outputs that can drive a separate host computer. One notable feature of the MCI is that its output response and sensitivity are programmed by the individual user to fit his range of motion and desired posture. As a safety feature, the MCI can detect when the encoder is "out of range" (should the encoder fall from the user's mouth), and can be programmed to respond appropriately when controlling a particular device.

In its current embodiment, the encoder unit is a three-segment, parallel-linkage arm. A pair of Hall-effect transducers is placed inside each segment, and measures the relative motion of the parts of the linkage. The encoder translates three-dimensional (3-D) head movement into three independent analog outputs and uses breath sip/puff signals to provide a fourth proportional control channel. Fitted with a mouthpiece, the encoder can be mounted on the wheelchair of the user, or directly on the user (i.e., a yoke that fits over the shoulders).

For the purpose of controlling the robot, the MCI emulates the action of a hand-held mouse. Seated comfortably in a wheelchair, the user grasps the encoder mouthpiece in his mouth, whereupon the segments of the encoder deflect in response to head motions. Side-to-side head movements are translated into horizontal movement of the cursor on the computer screen. Similarly, up-and-down nodding motions produce vertical movement of the cursor. A puff into the mouthpiece is translated into the mouse "click" action.

Robot command modes

Command modes for the robot can be classified within a hierarchy beginning with forward kinematic control, proceeding to inverse kinematic control, and ending with path and task planning (**Figure 3**). One layer of the hierarchy builds upon the next; high-level navigation and manipulation tasks can be decomposed into sequences of lower-level forward and inverse kinematics commands and sensing operations. The hierarchy reflects the distribution of effort between the user and the robot. As the robot becomes more autonomous by using the higher-level control, the burden on the user becomes less. The robot control software reflects this hierarchy.

Control panel

Forward kinematic commands are generated by a Teleoperator control panel (**Figure 4**), a computer graphic window filled with rows of "buttons" and "sliding indicators" (sliders), which when activated (clicked on) by the user, cause a joint movement command to be transmitted to the robot. In the incremental operation mode, a particular joint motion button specifies the joint and direction of movement, and the corresponding slider is set to indicate the desired amount of incremental movement of the joint. For instance, when the user clicks on the "arm dn" button with the corresponding slider set at "15," the arm

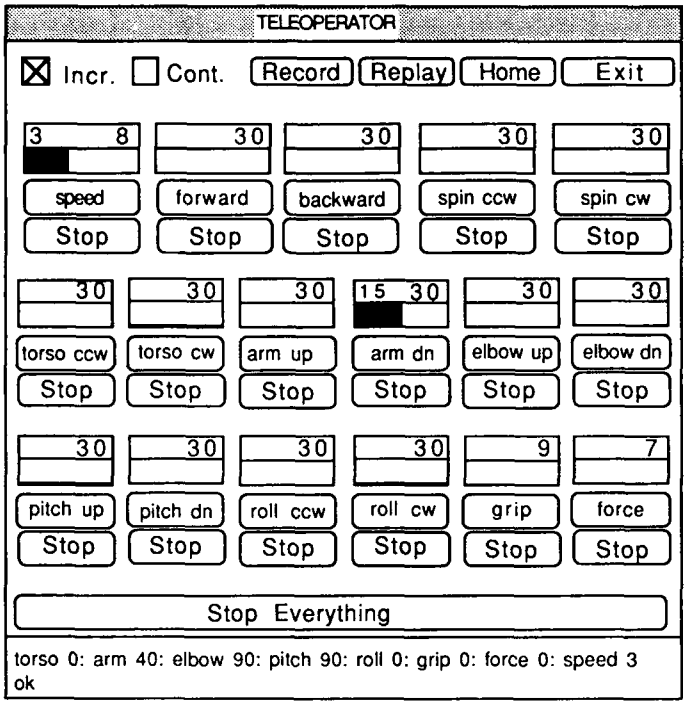

Figure 4.
Teleoperator control panel for forward kinematic control.

joint is caused to move down by 15 degrees. A "continuous" mode can be selected in which activity is initiated with a click on the joint motion button, and terminated only after a subsequent click on the corresponding "Stop" button is made, or after the joint has reached the limit of its range of motion. The individual "Stop" buttons as well as the large "Stop Everything" button provide a means for halting robot motion in an emergency situation.

Inverse kinematic commands and world modeling

Inverse kinematic commands, those that involve positioning the gripper and base of the robot with respect to a predefined global reference frame, are generated with the aid of a world model (a database containing information about the robot and its surroundings). Currently the environment of the robot is assumed to be static, structured, and indoors. Database creation and management are facilitated by means of an interactive graphics interface written in Object-Oriented LISP (**Figure 5**). The interface is designed to operate much like commonly available graphics applications such as MacDraft or MacDraw, possibly facilitating training of experienced Macintosh users. Using a palette of primitives which represent real-world objects, the user first creates a model of the robot and its environment. Though fully three-dimensional, the model is displayed as a two-dimensional top-down view. Selected objects appear with a graphic window and can be sized and positioned using cursor action or keyboard data entry.

Once the model environment has been given sufficient detail to define a set of task paths, commands for the real robot are generated either by selecting from a menu of possible actions, or by manipulating the model robot in a manner indicating the desired task. The robot itself is modeled as a combination of two primitive objects, a base and a gripper. Given a description of the dimensions and joint ranges of the robot, the workspace of the gripper within a horizontal plane is calculated as a function of gripper height and is displayed as a shaded region (**Figure 5**). The gripper object can be dragged to a new location within the workspace, resulting in the generation of commands which move the real gripper within the horizontal plane. A slide is used to specify the desired vertical position of the gripper. In an analogous manner, the base object can be dragged to a new location within the model environment, and assuming a clear path to the new location exists, a series of navigational commands will be issued to the real robot to move it to the corresponding new real location. The concept of generating commands for a real robot based on manipulation of a model robot is termed "model-reflective command generation" (14).

Because the robot itself is modeled, in theory any robot can be used in this system. In practice, the kinematics of robots are relatively easy to model, and solutions exist for numerous configurations. The major remaining tasks are those of translating and transmitting commands generated in the Teleoperator control panel and World Modeler in a syntax the particular robot understands, an endeavor that is facilitated by the modular nature of the control software.

Robot localization and path planning

In order for the robot to move about its environment autonomously, the robot must be able to establish its location and be able to chart safe courses within the environment. One method of localization uses the light sensor of the robot to detect the bearings of three or more controllable (by means of the X-10) light sources at known positions within the environment. By using the light positions as input, the robot can calculate its position and orientation by triangulation (15). Given a static environment in which the locations of all objects are known, an artificial intelligence search routine known in the literature as the A* algorithm is used to determine a shortest safe path between the current position of the robot and a user-defined destination point (16,17).

Robot safety

Safety standards in the field of industrial robotics have

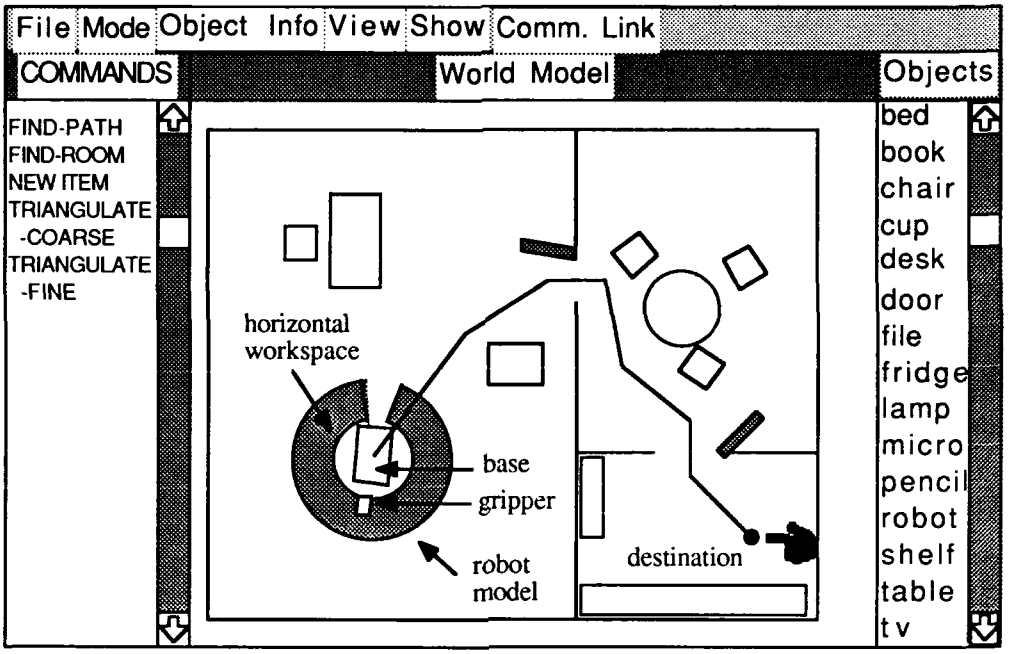

Figure 5.
World Modeler window for inverse kinematic commands and path planning.

been developed in the United States by the Robotics Industries Association (18). Industrial robots move at high speeds, can exert considerable forces, and can possibly surprise and crush an unwary operator. Therefore, safety regulations are aimed at keeping people away from a robot while it is moving and limiting any interaction by an operator with the robot under training conditions. Features such as panic buttons and dead man switches halt robot motion, while light curtains and enclosures prevent access into the workspace of the robot.

While robot safety has been the topic of recent discussions at professional society conferences such as the Rehabilitation Engineering Society of North America (RESNA), no such standards yet exist for personal robots, which by their nature are meant to interact closely with humans. In this project, a hardwired emergency stop on the MCI and software emergency stop buttons in the control panels provide means for halting robot motion. Also, the robot selected for this project possesses neither great speed nor great strength, so that if the robot operates away from the face of a user, the possibility for serious injury is minimal.

Laboratory testing and demonstrations

Laboratory testing of the robotic system is ongoing as new software features are written. Preliminary testing took place in the Mechanical Engineering Robotics Lab at Rice University and at The Institute for Rehabilitation and Research (TIRR) in the Texas Medical Center. The MCI and robot systems were demonstrated at the 1987 RESNA Conference; the MCI was used to command the robot in teleoperator mode to move cups and other small objects between the floor and a table.

Testing of the localization and path planning routines, in combination with the wireless modem link has been carried out in offices and adjoining hallways in the Mechanical Engineering building at Rice University. A world model of the entire second floor of the building was created, with details of the desks, chairs, shelves, and lamps in one of the included offices. Using the model, the position of the robot and its orientation within the office could be determined to within 6 inches and 5 degrees, although the inverse trigonometric equations used in triangulation have multiple solutions that can produce erroneous results. The robot successfully traversed paths extending from the office into the hallway. The range of the modem link was exceeded and communications lost if the robot traversed more than 100 feet from the base unit. World modeling, model reflective command generation, path planning, and untethered operation via the RC were demonstrated during the Space Operations Automation and Robotics (SOAR '89) conference at NASA/JSC.

In-home testing

Beginning in March 1988, the robot and MCI were placed in homes of volunteers with severe physical disabil-

ities. At that time, the robot was tethered and none of the autonomous features had been developed. Five subjects, two women and three men, ranging in age from 20 to 46 years, used the system. All subjects had previous computer experience. Depending on scheduling and the level of interest of each subject, the robot remained in the home of a subject for a period of time ranging from 1 day to 6 weeks. The equipment was transported to the home and set up by laboratory personnel. Training was done at the time of installation, and lasted about 2 hours. The user was familiarized with the boot-up procedures for the system with the help of a two-page manual, and given a brief explanation of the Macintosh operating system, the MCI, and the control software for using the robot in the Teleoperator mode. The user was given several tasks to accomplish to assure that the system was working and the user understood the training. These tasks included opening a hinged door, moving a drink container from one surface to another, and picking up paper from the floor.

Each of the subjects was able to make the robot perform useful tasks that increased their personal autonomy, as reflected in their ability to arrange and retrieve objects in their environment without the help of assistants. As a matter of safety, tasks involving movements of the robot near the face of the user were discouraged. Such tasks include feeding and personal hygiene. The robot was designed primarily as an assist to retrieve dropped objects, to move objects in the environment (e.g., a book or a glass), and to open hinged doors. These tasks were selected from a prioritized list of tasks generated by users in the Houston area. Typically, users experimented with moving cups and other small objects about their living quarters.

The subject who used the MCI over the most extended period of time found the robot to be compatible with the MCI. Subjects found the control software easy to understand and use in conjunction with the MCI. Some users were able to operate the system using the standard mouse rather than the MCI.

During this testing, the subjects noted several areas that needed improvement. The robot was found to be cumbersome to move about the room due to its tether and to the incremental nature of commands generated in the Teleoperator mode. Those who were able to use the RC to control the robot found the RC too slow and unreliable to be useful. The time required to perform a single pick-and-place task was rather long, often in the range of 5–10 minutes. Hence, the users felt that if the robot was easier to move and required fewer commands to operate, it would be a more useful tool. All users indicated that they would be interested in purchasing a robot once a simplified means of commanding the robot existed. It was on the basis of these experiments that the higher-level command software was developed. Using the World Modeler, the number of commands required for operation was reduced and tasks can now be accomplished efficiently in shorter periods of time.

The World Modeler system has been evaluated by one user, a person who had used the system the longest during the first in-home testing, and many of the problems inherent in the first generation system have been solved. The robot can be moved more quickly, typical travel times are now only 3–6 minutes for trips in an apartment. This time reduction and higher-level gripper-control function have made it possible for the user to perform pick-and-place tasks in as short a time as 2 minutes. By utilizing the robot to move items at a workstation, the user has enjoyed greater personal autonomy, and the time required to do a task is less than or equal to the time segment required to accomplish the same task using a shared attendant.

DISCUSSION AND CONCLUSIONS

The ultimate measuring stick of an assistive device is its utility to and use by the user in combination with its affordability. In developing robotic aids, various researchers have approached the question of cost/utility trade-offs from different perspectives. Some have started with high-end, industrial grade equipment and "tamed" the equipment to work in domestic or office environments. Others, such as the authors, have started with low-end, educational grade equipment and added improvements. Work must continue toward a middle ground of improved utility and decreased cost, demonstrating what can be done with all commercially available technology and, most importantly, giving end-users a range of options. In this light, several important conclusions arise from the current project:

1. Inexpensive, off-the-shelf robotic and computer technology is available that can increase the personal autonomy of the severely disabled individual. Before robotic technology will fulfill its potential for disabled people on a larger scale, a more reliable, low-cost robot must be available.

2. The Machine Control Interface is a powerful, cost-saving component. The MCI provides a user-programmable all-in-one unit for controlling a variety of electromechanical devices, including wheelchairs, computers, and the robot.

3. A Macintosh or other PC can provide the framework for a system to command a mobile robot in an indoor, static, structured environment. With thoughtful planning,

areas in the home of a severely disabled user can be made into such an environment.

4. Object-oriented LISP provides a powerful, compact structure for representing the real world and for implementing advanced problem-solving routines related to robot autonomy.

5. At the time of this writing, the HERO 2000 is no longer commercially available. Regardless, the concepts of operator control panel, world modeling, and model reflective command generation can be applied to any mobile robot.

ACKNOWLEDGMENT

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A Technical Note

Development of an automated wheelchair guided by a magnetic ferrite marker lane

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Abstract—An automated wheelchair with a guide sensor, guided by a magnetic ferrite marker that is resistant to the presence of dirt, is described. The wheelchair permits the severely disabled, as well as the older population, to move about freely, both indoors and outdoors. This is due to the simple operation involved (pushing a button), and a magnetic ferrite marker lane which is minimally influenced by dirt or other nonmagnetic materials. For increased comfort, a nonlinear signal-processing circuit and pulse-steering drive method have been developed to provide a smooth running operation. In addition, a function that provides for stopping at desired destinations has been added for convenience, and a collision prevention function using infrared sensors has been added for safety.

Key words: *automated wheelchair, biomechanics, ferrite marker, magnetic sensor.*

INTRODUCTION

In response to the demands of wheelchair users for equal access, hand-propelled wheelchairs, electrically-controlled wheelchairs, and automated-guided wheelchairs (AGW) have been developed. However, because upper body strength is required, a hand-propelled wheelchair does not permit an older or severely disabled person an extensive range of travel. An electrically-controlled wheelchair can be controlled by a manually-operated joystick—but because this type of wheelchair sometimes zigzags, and a slight movement of a joystick can cause a quick turn, driving an electrically-controlled wheelchair requires the operator to be skilled both in turning, and in direction-change operations—especially on narrow or curved roads. Therefore, it is difficult for many severely disabled and/or elderly persons to operate them skillfully.

Conventional AGWs, which are guided by reflective tape markers laid on the road or floor, are influenced by dirt on the tape. That is, when reflective tape markers are coated with dirt or mud, the photo-detection sensor (with photo diodes) installed on the wheelchair cannot discriminate these markers from the surrounding road or floor surface; therefore, the user cannot control the steering wheel, making this type of wheelchair difficult to use.

In addition to the photo-detection guidance technique for the AGWs, other automatic vehicle guidance techniques, such as visual machine guidance and buried-wire guidance systems might be used (1). As a visual machine guidance technique, optical guiding along a painted track, using a video camera, has been proposed (2). Since much processing time is necessary for this guidance system to recognize the position of the track in front of the AGW, it is impossible to move very fast; this technique is also not useful in a dirty, rain-covered, or snowy environment, because the camera cannot recognize the track covered with dirt or snow.

When using a buried-wire guidance system, if the wire is cut for some reason, it cannot operate due to lack of a magnetic field generation. Changes in the guidance lane location are awkward because the wire must be buried. Therefore, in addition to a high implementation cost, this guidance system lacks reliability.

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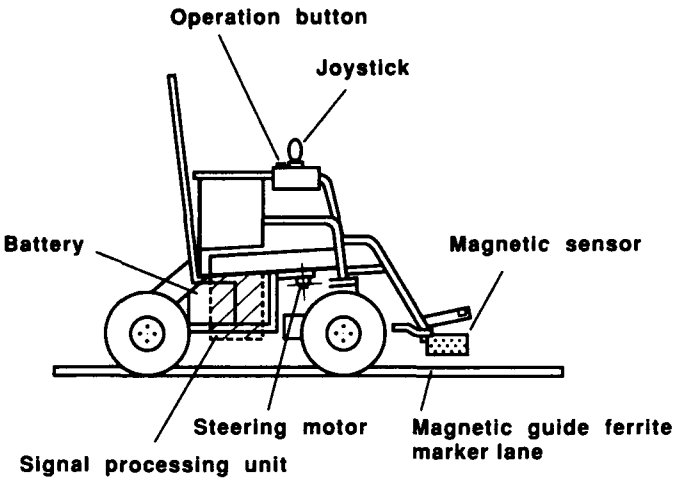

Figure 1.
Automated guided wheelchair configuration.

The magnetic ferrite marker technique is useful because the vehicle can move relatively quickly (due to simple recognition of the marker position by magnetic sensors) and is not influenced by a local marker being cut off (3).

This paper describes an automated wheelchair guided by a magnetic ferrite marker which is relatively free from adverse influence by dirt or mud and because of its simple operation, permits easy use by severely disabled and older people (4). This wheelchair would be especially useful for mentally alert people with severe motor impairment (e.g., quadriplegics and cerebral palsy patients), since it allows them to move wherever they want to go along a laid-out route, merely by a simple push-button operation. A nonlinear circuit and a pulse-steering drive method (developed to achieve a smooth running operation), an infrared sensor system for stop operation, and safety functions are described. Investigation results were derived from the running characteristics of this wheelchair.

GUIDANCE TECHNIQUE PRINCIPLE

Figure 1 shows an AGW with a magnetic sensor guided by magnetic ferrite markers which are laid in/on the sidewalk or floor (3,5). Any electric motor-driven wheelchair can be partially modified by installing the magnetic sensor, signal-processing circuit, and operation button, allowing a change in its mode of operation. The magnetic sensor is installed under the footrests at the front of the wheelchair to control the steering wheels. This sensor, which is 7 cm from the road surface or floor, picks up guidance signals from magnetic ferrite markers. The magnetic ferrite marker lane, using soft ferrite material bound in place with resin, is 10 cm wide, 5 mm thick, and can be extended as far as necessary.

Figure 2a shows the magnetic sensor and ferrite marker configuration. **Figure 2b** shows the magnetic sensor signal-processing circuit. The magnetic sensor consists of an exciting coil, *L*, at the center of the sensor unit and two detecting coils, *L1* and *L2*, placed on its right and left sides. Exciting coil *L* generates a magnetic field. The ferrite marker is magnetized by this field and sets up a new resonant magnetic field; the result being that the original magnetic field is deviated. Detecting coils, *L1* and *L2*, pick

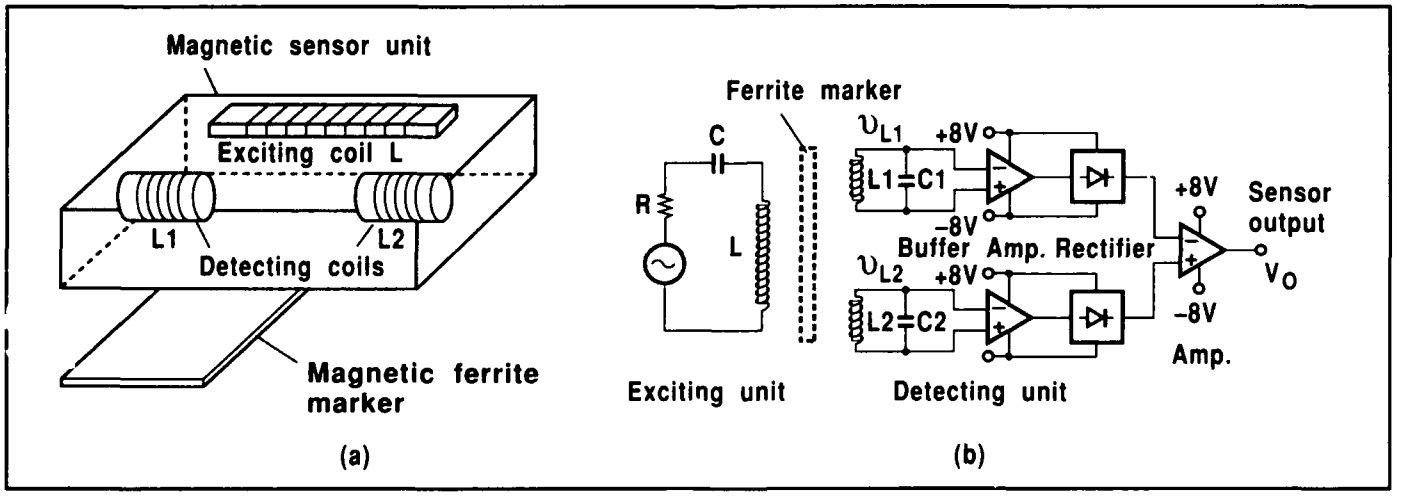

Figure 2a.
Magnetic sensor. System configuration.

Figure 2b.
Magnetic sensor: Signal-processing circuit.

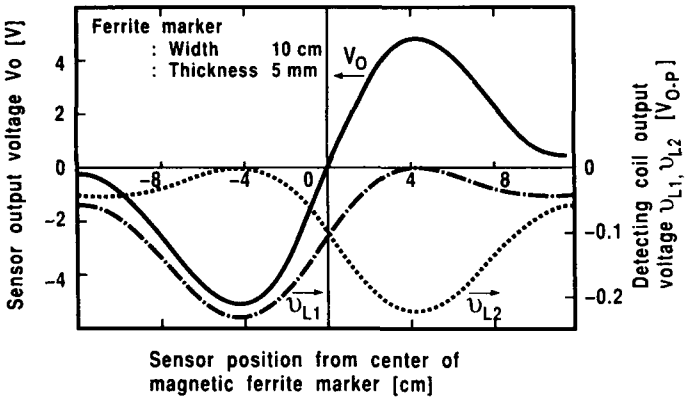

Figure 3.
Detecting coil- and sensor-output voltage versus sensor position.

up the magnetic field deviation. The detected output signals obtained by two detecting coils, V_{L1} and V_{L2}, reduce linearly, as shown in **Figure 3**, as the sensor position deviates from the center of the marker lane. These signals reach a peak level and then reduce to a small value as the sensor position deviates further. These characteristic signals cross at the center of the marker lane. These output signals are subtracted from each other to obtain an S-shaped characteristic, suitable for use as a steering control signal. As a result, since the sensor output signal (i.e., the difference between these detection-output signals), is proportional to the wheelchair deviation from the center of the ferrite marker lane in a line or curved form, the difference signal permits controlling the movement direction of the wheelchair. For example, consider the case where the sensor position deviates slightly from the center of the marker. When the sensor output signal voltage is increasing to a higher positive level, a controller for governing the steering motor rotation direction permits it to rotate the forward wheels in such a direction as to bring the sensor position back to the center of the marker lane. When the sensor output voltage is decreasing to a lower negative level, the controller permits the forward wheels to rotate in the opposite direction. Thus, the wheelchair can be controlled in a route approximately along the center of the marker lane by using the magnetic sensor.

NEW TECHNIQUES FOR HIGH LEVEL PERFORMANCE

Safety, comfort, and convenience are very important for wheelchair users: therefore, several considerations are required to realize a high-level performance wheelchair system.

Smooth running operation for comfort

In order to provide a comfortable ride, a partially steering-free operation by a nonlinear circuit and pulse-steering drive method was developed.

In general, when the wheelchair's steering is controlled according to a sensor output signal indicating sensor positions (steering angle changes linearly with the sensor output signal), the wheelchair movement tends to oscillate slightly. This oscillation phenomenon occurs when a system, including the sensor, signal-processing circuit, controller, drive motor, drive wheels, and magnetic marker, is set up for a certain oscillation condition. The magnitude of the steering angle changes almost linearly with the sensor output signal. Since a steering control signal (sensor output signal) is applied continuously to the wheelchair, it is almost immediately brought back toward the center of the route whenever it deviates slightly from the center of the marker. In this case, the wheelchair could move from side to side at a certain variation rate (a relatively higher perturbation frequency than a few cps). When this return operation frequency matches and reinforces a system oscillation frequency, the result is the system oscillation frequency being different from the ordinary intermittent and irregular steering control state. Once the system starts spurious oscillating, it is difficult for the system to shed this movement variation.

To prevent this wheelchair from wobbling during operation, a steering-free operation within a small deviation range (i.e., a small area along the center of the ferrite marker lane when the magnetic sensor deviates slightly) is realized by a nonlinear signal-processing circuit (**Figure 4**). This circuit consists of an amplifier and several diodes, used to shift about 1 to 2 V of the sensor output voltage point, when the steering control voltage rises. When switch A is on, about $\pm$1V steering-free operation voltage range is obtained. When both switches A and B are off, about $\pm$1.5V steering-free operation voltage range is obtained. Even when the magnetic sensor deviates within these steering-free operation ranges, accurate steering control is not immediately achieved. In this case, system steering control oscillation is retarded, because the return

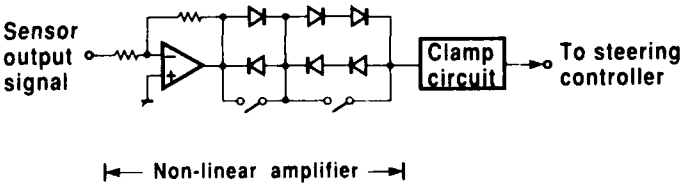

Figure 4.
Nonlinear signal-processing circuit configuration.

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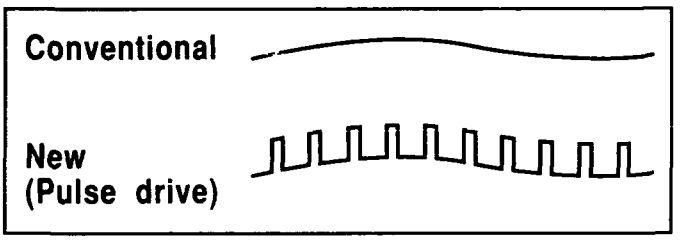

Figure 5.
Steering drive pulse in pulse-steering drive method, compared with conventional drive method.

operation from side to side becomes slower than the oscillation, enhancing safe driving.

The wheelchair also has a tendency to zigzag (not oscillate) due to any quick movements of the steering wheel when partially steering-free operation is achieved by the nonlinear circuit. That is, after the steering angle rises sharply when steering control starts in a conventional continuous steering drive method, subsequent steering movements continue to be controlled within the steering operation ranges. Therefore, the steering wheel movement sometimes overruns to the other side and follows a zigzag course. If the wheel movement inertia moment is too large at a subsequent change in its movement direction by the steering control signal, the wheelchair cannot change this moment direction immediately. This zigzag running is a slow movement with a large arc locus and differs from the above mentioned oscillating operation.

To minimize this zigzag running to the smallest extent, a new pulse-steering drive method is used within a small steering wheel deviation range. With the pulse-steering drive method (**Figure 5**), intermittent drive pulses are added to the sensor output signal and passed through the nonlinear circuit. As a result, steering is gradually changed from a lower sensor output voltage than that required for the steering-free limit (does not cause steering to change greatly when steering control starts). The intermittent drive pulse variation consists of a positive pole pulse, when the sensor output signal is positive, and a negative pole pulse, when the sensor output signal is negative. Its variation frequency is 10 times per second (with a 10 percent to 25 percent duty range). With this drive method, a gradual steering control is achieved. When the wheelchair deviates a little from the center of the marker lane, the control steering angle is set relatively small. As it deviates further from the marker lane center, the steering control angle becomes relatively greater. Thus, a delicate steering wheel angle control is possible and is not expected to cause overrun. As a result, the wheelchair will move smoothly without zigzag running.

Automatic stop operation for convenience

People who use wheelchairs may be severely visually-disabled or lack the full use of their hands. When the user needs to move to several destinations in sequence, the automatic stop operation is required at specified positions. (This route can be set up before wheelchair movement starts.) To permit the wheelchair to stop automatically at desired destinations, an infrared position detection sensor system has been constructed which detects the reflection tape previously placed at the destination (laid on the floor or sidewalk). The reflecting tape material has a different reflection coefficient from that of the surrounding floor or pavement surface. In experiments, road sign reflecting material now on the market was used as reflecting tape. When the position detection sensor on the wheelchair detects this reflecting tape, it automatically stops the wheelchair movement.

When there are several destinations, the sensor counts the number of tape markers as the wheelchair passes them so that the user can move easily to a desired destination.

Emergency stop operation for safety

Maintaining safety is important for every user. To prevent a possible collision with people, chairs, animals, etc., two infrared obstacle detection sensors were constructed on the front of the wheelchair. When an obstacle appears in front of the wheelchair, it detects the obstacle, stops, and remains stationary until the obstacle is moved out of the path of the wheelchair.

Figure 6 shows a control circuit block diagram. A selection switch used to select either automatic mode or manual mode is provided for achieving flexible movement. (For example, the manual mode allows users to operate the wheelchair even in locations where the marker lane has not been laid out.) In the automatic mode, an automatic-manual selection switch circuit permits current to flow in an electromagnetic relay and selects the automatic mode. In this case, the magnetic sensor output signal is used for steering control through the nonlinear circuit and the pulse generator. Also, the velocity, predetermined in a velocity regulation part, is used for drive motor speed control (front wheel movement speed control).

However, when an obstacle or position detection sensor detects either an obstacle in the path or reflecting tape laid at the destination, the operation mode is automatically changed to manual mode and the wheelchair stops. The joystick is held in the center of its control area and steering- and drive-motor control signals, supplied from a handle operation, are not present. In the manual mode, steering and speed are completely controlled by operating the joystick.

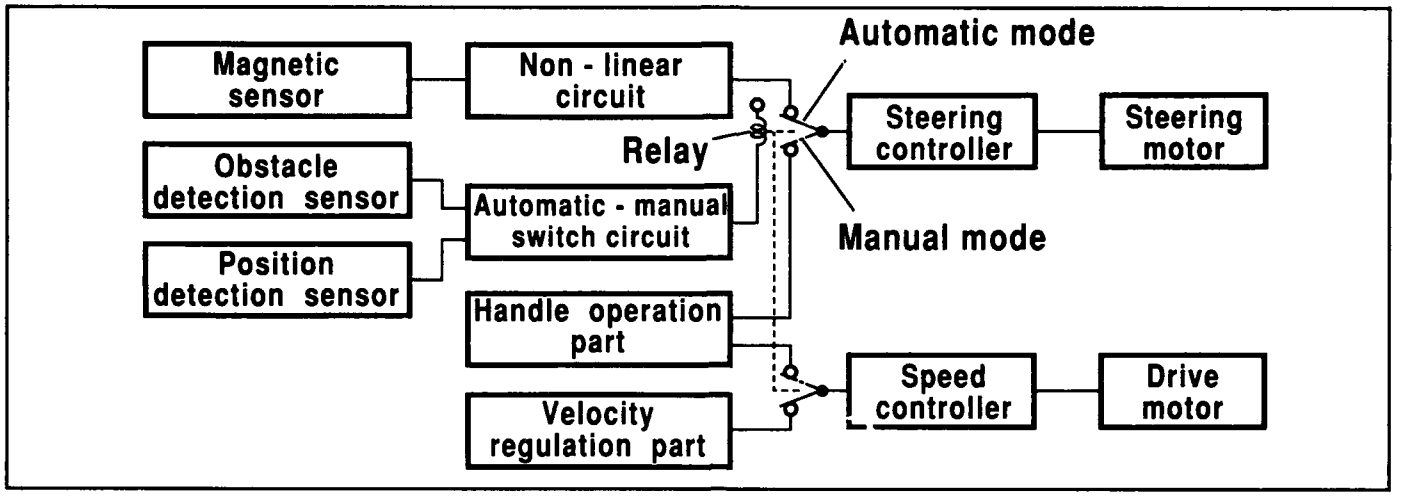

Figure 6.
Control circuit block diagram.

RESULTS

The automated wheelchair, with the magnetic sensor on the front (under the footrests) is shown in **Figure 7**. Running experiments were carried out along a corridor with a soft ferrite marker on the floor. **Figure 8** shows the infrared position-detection sensor installed on the left side of the wheelchair (about 25 cm above the floor), and the reflection tape marker laid on the floor. When the automated mode is selected, the wheelchair movement is started by pushing a button which has been installed on the back of the joystick console box.

Figure 9 shows the steering angle versus the sensor output voltage, realized by using the nonlinear circuit and the pulse-steering drive method. Circuits 1 and 2 have different gains and their diodes have nonacting zones in the nonlinear circuit, giving ± 0.9V and ± 1.4V sensor output steering-free operation in the voltage area. The wheelchair did not oscillate in either case, since steering was not controlled within these areas. However, a wheelchair with such a nonlinear circuit showed zigzag running when gradual steering controls were not used.

The gradual steering control method caused a steering angle change, gradually changing from about ± 0.5V. The wheelchair with this gradual steering control method did not cause overrun (zigzag running). In this case, it successfully ran along the marker at less than 4 km/h, even when carrying a 180 kg load. At higher speeds, a slight zigzag running phenomenon was observed, which should improve in the future.

When an obstacle appeared about 2 meters in front of the wheelchair (the infrared sensor-detection range), it

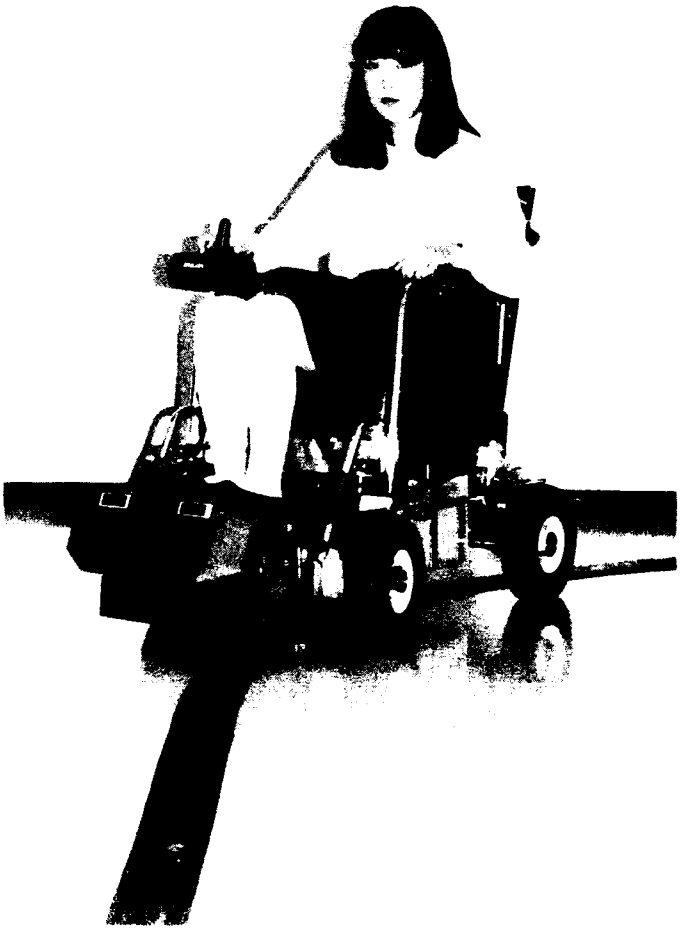

Figure 7.
Automated wheelchair during running experiment. Two infrared obstacle detection sensors are installed at the front.

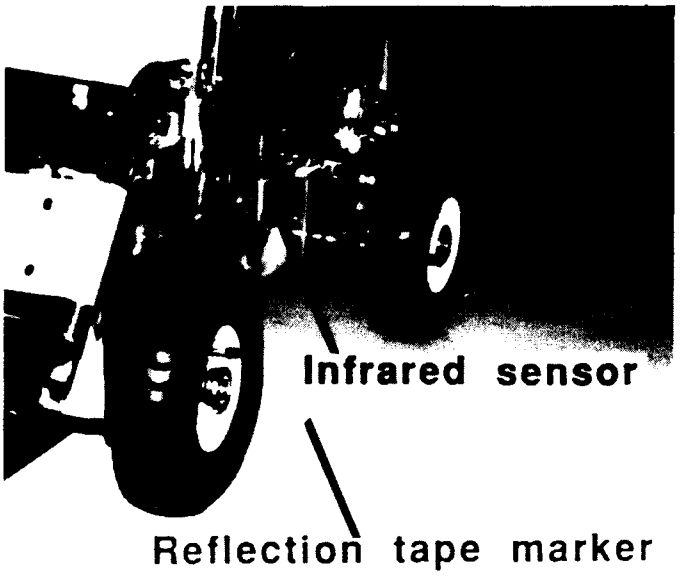

Figure 8.
Infrared position detection sensor and reflecting tape marker used to stop the wheelchair at specified positions.

came to a stop safely. The wheelchair also comes to a stop at a predetermined position along a set route when detecting previously-laid reflection tape.

Thus, this wheelchair moved without zigzag at less than 4 km/h walking speed, and automatically stopped at the desired destination; also, obstacles were accurately detected and collision safely prevented. This wheelchair system was exhibited at the *Second International Home Car & Rehabilitation Exhibition* held in Japan in 1988, and many people experienced its performance at less than 4km/h along a track route with a 2.5 m radius. Specifications including other features for the automated wheelchair are shown in **Table 1**.

DISCUSSION

Because the magnetic ferrite marker is used as a guide lane and has a strong magnetic property, it becomes momentarily magnetized by an alternate magnetic field (about 40 kHz). The resonant field can be picked up by the magnetic sensor without being influenced by dirt or small nonmagnetic materials left around and over the ferrite marker. This characteristic is different from that of the photo-detection technique (with photo diodes) used for a conventional AGW. A Charge Coupled Device (CCD) camera system can be used as another sensor in the photo-detection technique. However, because this system picks up the same signal as the conventional reflective tape marker, an AGW with this CCD camera system is easily influenced by many kinds of dirt coated or dotted on the marker.

Dynamic modeling of the wheelchair system using microprocessors was investigated (6,7). In this wheelchair system, it is necessary to construct a software program for computing control algorithms and sending steering control signals to a steering motor control part. The initial development cost for the software program seems to be high. On the contrary, an analog controller using the nonlinear circuit is easily constructed and its development cost is low. However, if the packaging of software for the steering control system with microprocessors progresses, the development cost will be reduced in the future and may be applied to this automated wheelchair with a magnetic sensor for outdoor use.

This wheelchair is available for forward or turn-back movement along a single guidance route (a ferrite marker lane). Performance is sufficient for practical use, especially outdoors. When microcomputers are installed in the future, the wheelchair will be able to move along a more flexible route. For example, even if there were some branch points along one marker lane, the wheelchair can be controlled to move anywhere the user would like to go by detecting markers at the branch position.

Also, even when the routes are composed of alternate ferrite marker lanes, the wheelchair can run along such routes. In this case, in the gap between two adjacent marker lanes, the wheelchair moves autonomously with the steering control (without the detection of the magnetic marker).

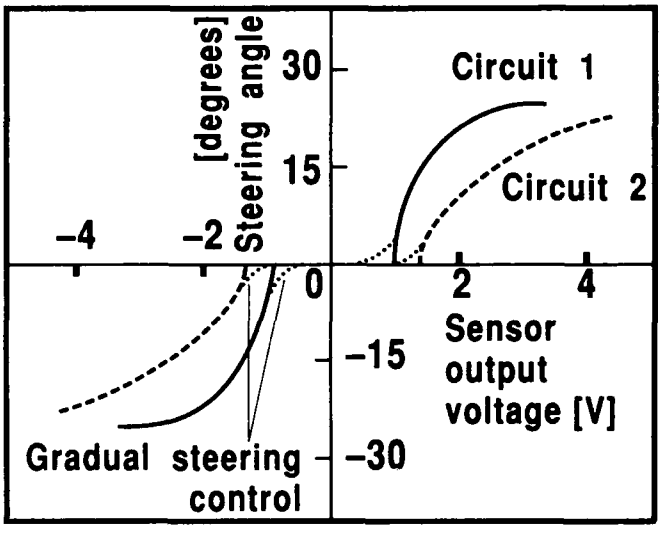

Figure 9.
Steering angle versus sensor output voltage characteristics determined by a nonlinear circuit and a pulse-steering drive method (gradual steering control).

Table 1.
Newly developed wheelchair specifications.

No.	Item	Specifications
1	Guidance	Magnetic guide method with ferrite marker lane
2	Movement mode	Automatic mode (manual mode possible)
3	Drive method	Front wheel direct drive
4	Drive control method	3-stage speed change by switch
5	Brake	Electric brake and dynamoelectric damping brake by drive motor
6	Steering control	Front wheel power steering
7	Practical uphill angle	About 7 degrees
8	Maximum level difference to be overcome	About 6 cm
9	Minimum rotation radius	2.5 meters
10	Running speed	Max. 2.2km/hour
11	Battery	12V × 2
12	Battery charge	Automatic charging method with electronic timer
13	Drive motor	Max. output power 24V 180W × 2
14	Weight	About 70kg
15	External dimensions	122.5cm Length × 56cm Width × 78cm Height
16	Permission running time on flat areas	About 4 hours

Since this system depends on detecting a route for movement control, when it cannot detect a sensor output signal within a certain distance, this gap is limited to a shorter distance than the minimum moving distance in the course. When the wheelchair changes the present route to some other route, it detects crosspoints on the ferrite marker lanes at possible route change locations. It then moves along the route in the desired direction. By using these alternate routes, the system cost reduces to a point lower than the cost for a single route. In these cases, the activity range for users will be greatly increased.

CONCLUSION

An automated wheelchair was developed with a magnetic sensor used for guidance. It was automatically guided by a magnetic ferrite marker laid in/on the sidewalk or floor. This AGW allowed the user to move about by merely pushing a button. Due to the partially steering-free operation, realized by a nonlinear circuit and a pulse-steering drive method, it showed a satisfactory high-running performance (safe, comfortable, and stable-running). Convenient automatic stop functions used at desired destinations were the result of an infrared sensor for detecting a reflecting tape marker, as well as for stopping at prescribed positions. A temporary stop function for assuring driving safety resulted from providing two infrared sensors for obstacle detection and for stopping.

Because the ferrite marker is not influenced by dirt or other small nonmagnetic materials on the marker, it is applicable both indoors and out of doors. This easily operated wheelchair using such a marker increases the activity range for users. This will be especially important in the future, when the average age of the user will be higher.

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Safety studies with the University of Melbourne multichannel electrotactile speech processor

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Abstract—Results of safety investigations conducted as an integral part of the development of a multichannel electrotactile speech processor (Tickle Talker™) are reported. Electrical parameters of the stimulus waveform, design of the electrode handset and cabling, and the electrical circuitry of the speech processor/stimulator and programming interface have been analyzed for potential risks. Constant current biphasic square pulses delivered to electrodes positioned on the skin surface over the digital nerve bundles were chosen to optimize the safety, comfort, and function of the electrotactile stimulus. The device was battery-powered, and the user circuit was isolated from earth-referenced sources. Each electrode was isolated by capacitive coupling, preventing DC leakage of current to the user circuit. Studies of finger temperature showed slight cooling of the skin on the fingers of both stimulated and unstimulated hands for individual subjects following electrotactile stimulation through the Tickle Talker. Subsequent analysis of finger and hand vascular circulation in five subjects showed slight reductions in hand blood flow in some individuals. The results did not demonstrate a significant mean decrease in hand or finger blood flow following electrotactile stimulation. No evidence of sympathetic involvement was found, nor were any changes in vascular structure of the hand such as those associated with Raynaud's disease found. Evidence suggests that the decrease in temperature found in the initial study may be due to a change in the ratio of blood flow between arteriovenous anastomoses and nutritive capillary beds. Studies of: 1) changes in mean threshold and comfortable pulse widths over time; and, 2) changes in tactual sensitivity as measured by hot/cold, sharp/dull, and two-point difference limen discrimination, did not detect any systematic change in peripheral nervous system function following electrotactile stimulation. Analysis of electroencephalogram (EEG) recordings taken during electrotactile stimulation, and after relatively long periods of experience with the device did not show any pathological changes which might be associated with epileptic foci. In summary, no contraindications to long-term use of the Tickle Talker were detected in the studies performed.

Key words: *electroencephalogram (EEG), electrotactile stimulation, hand blood flow, hearing impairment, multichannel electrotactile speech processor, plethysmograph temperatures, Tickle Talker™.*

INTRODUCTION

Since the 1920s, researchers and educators of the deaf have sought to develop sensory aids to assist communication for the hearing-impaired (1). Exploited sensory modalities have included vision, touch, and more recently, direct neuroelectric stimulation (2,3,4). While improvements in open-set word, sentence, and conversational speech perception have been reported for both children and adults using cochlear prostheses (5,6,7,8), the necessity of surgical intervention for implantation has led to a renewed interest in development of noninvasive means of providing sensory input, especially in the case of children (9).

Research has established that speech information may be conveyed as tactual patterns, and that this information can be integrated with input from vision or aided residual hearing to improve speech perception as measured by

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feature, word, or sentence tests (10,11,12,13,14). Tactual displays developed to date differ in number and location of transducer sites, type of speech information transmitted, and methods of encoding this information. Despite numerous reports evaluating feasibility and potential benefits available from vibrotactile or electrotactile devices, investigation of potential hazards arising from everyday use of these devices over long periods has been overlooked. This contrasts with cochlear implant development, which has included stringent biomedical safety studies required by the surgical procedure involved (15).

Although use of tactile devices involves no surgical risks, unforeseen problems may arise after prolonged use, especially in the case of young children. Despite the lengthy history of vibrotactile aid development, with few exceptions (16), evaluations have been of tactile users having relatively short periods of training and experience with vibratory stimulation. In addition, systematic studies establishing the safety of the vibratory stimuli used have not been reported. Psychophysical aspects of electrical stimulation have been examined in the development of electrotactile devices such as the Tacticon 1600, however no evaluation of long-term safety issues relating to use of this particular device has been reported (17,18). Given that multichannel tactile devices are viewed as a potential alternative to cochlear implantation for some subject groups, a clear responsibility lies with the developers and manufacturers of tactile devices to ensure that they are not only effective as speech perception devices, but also biomedically safe for long-term use.

In 1985, Blamey and Clark (19) first described a wearable, battery-powered multiple-channel electrotactile speech processor (Tickle Talker™), which used electrical stimulation of the digital nerve bundles in the fingers of the nondominant hand to present speech information. Novel features of this device were use of nerve bundle stimulation in contrast to stimulation of peripheral nerve end organs, and use of a formant-based speech processing strategy similar to that used in the University of Melbourne/Cochlear 22-channel cochlear implant. Psychophysical studies demonstrated that placement of electrodes on the skin overlying the digital nerve bundles resulted in a more comfortable sensation, with larger dynamic ranges than for electrical stimulation at other body sites (20). These findings were consistent with physiological studies showing nerve fiber stimulation to be characterized by different evoked sensations than stimulation of nerve end organs (21). The digital nerve bundles in one hand provided a spatially distinct and well-ordered series of stimulus sites. In addition, use of the fingers had the well-known advantages that tactual sensitivity is maximal at the fingertips, and that cerebral representational area is proportionately larger for the facial region and hands. The nondominant hand was selected to reduce the possibility of the device limiting everyday functions of the hands.

This report summarizes the results of safety studies which have been conducted as an integral part of the development and evaluation program of the Tickle Talker. Aims of the studies were to: 1) assess the possibility of risks inherent in the electrical nature of the stimulus and device; and, 2) establish the safety of the device for long-term use by examining possible changes in physiology following use over an extended period. Assessment of the stimulus and device focused on safety considerations in the electrical parameters of the stimulus waveform, design of the electrode handset and cabling, and electrical circuitry of the speech processor/stimulator and programming interface. The longer-term physiological assessments included consideration of: 1) possible effects of electrotactile stimulation on local tissue, as measured by changes in tactual sensitivity, finger temperature, and finger and hand blood flow; 2) possible effects on peripheral nervous system function as measured by changes in threshold and comfortable level pulse widths over time; and, 3) possible effects on central nervous system function as measured by changes in electroencephalograms (EEG) during or following electrotactile stimulation.

SAFETY CONSIDERATIONS IN THE DESIGN OF THE DEVICE

Electrotactile stimulator

The device has been described in detail in previous reports (20,22). It consists of: 1) a wide-band omnidirectional microphone to receive speech input; 2) a speech processor/stimulator unit, in which speech features are extracted in a manner similar to that for the 22-channel cochlear implant (23); and, 3) an electrode handset which is used to present speech information to the user as a pattern of electrical stimulation. The microphone, speech processor and stimulator circuitry are powered by a single 1.5 volt AA alkaline cell, which gives from 8 to 12 hours of continuous use.

The handset includes eight electrodes (49 mm^2), positioned in rings worn on the four fingers of the nondominant hand, and located directly over the digital nerve bundles on the two sides of each finger. Several different materials have been used for electrode construction, including stainless steel mesh, stainless steel sheet, and platinum tubing. A single conductive rubber electrode (10 cm^2) is located

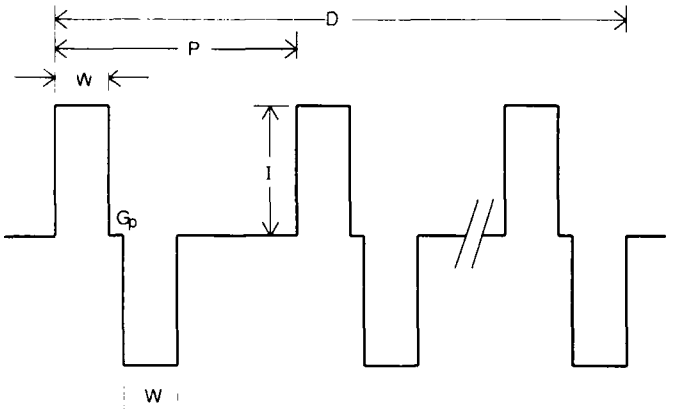

Figure 1.
Biphasic constant current stimulus waveform as used in the Tickle Talker™: D is the electrode stimulus duration; P is the period of each stimulus waveform; G_p=100 μs, the interphase gap between two phases of the stimulus on any electrode; I=1.5 mA, the fixed stimulus current; W is the pulse width of each phase of the biphasic stimulus over the range 10 to 1000 μs.

at the wrist. At any given time, current flows between one selected finger electrode and the wrist electrode. The electric current waveform (**Figure 1**) consists of biphasic, constant current (1.5 mA) square pulses. The two phases are separated by a 100 μs gap in which there is no current flow.

Three speech features are extracted in the speech processor and presented as tactual patterns: 1) the main spectral peak between 800 Hz and 6,000 Hz (an estimate of vowel second formant frequency) is encoded as electrode position, with low frequency sounds presented on the index finger, and high frequency sounds such as /s/ on the little finger; 2) the speech amplitude envelope is encoded as pulse width of the biphasic pulses, and sensed by the user as changes in strength of stimulus; and, 3) the fundamental frequency is encoded as a scaled function of pulse rate, and sensed by the user as changes in the quality of sensation. A computer interface and RAM allows threshold (T) and comfortable (C) pulse widths to be set and programmed independently for each electrode over the range 10 to 1,000 μs/phase. The processor also allows the pulse rate to be scaled so that a fundamental frequency of 250 Hz results in a pulse rate of 150 pps. Scaling of pulse rate was based on psychophysical studies which showed better discrimination of pulse rate changes at lower rates of stimulation (20).

Electrical stimulus considerations

For safe and painless electrical stimulation of the skin, it is necessary to avoid irreversible electrolytic processes at the skin/electrode interface (24), dielectric breakdown resulting in a few high current density channels across the skin (25), and large conversion of energy to heat (26).

A biphasic constant current stimulus waveform with equal charge in each phase is used in the Tickle Talker to ensure that there is no net current flow, and to reduce the possibility of irreversible electrolytic effects at the skin/electrode interface. A biphasic rectangular pulse waveform was selected on the basis of previous studies demonstrating its safety for biomedical applications (27). Limiting of the electrode current applied in each phase to 1.5 mA, flowing between the wrist and selected finger electrode, reduces the possibility of skin breakdown due to direct effects of the electrical stimulus. In addition, this level is well within established limits for electrical stimulation posing no danger to the myocardium (28,29). The charge varied from 15 nC to 1,500 nC/phase as the pulse width varied from 10 to 1,000 μs, representing a maximum current density of 3.06 $\mu C/cm^2$ geometric/phase. Biomedical safety studies of the University of Melbourne cochlear implant, using similar waveforms, have shown no damage to the neural tissue following prolonged intensive stimulation through implanted platinum electrodes with charge densities ranging from 20 to 40 $\mu C/cm^2$ geometric/phase (30). Other studies of implanted electrodes used in subcutaneous stimulus regimes have suggested that all charge may be injected by reversible chemical reactions up to a maximum current density of 300 $\mu C/cm^2$ geometric/phase (31). While care must be used in direct application of safety data developed for subcutaneous stimulation to the case of cutaneous stimulation, the charge densities used in the Tickle Talker are well below recommended safe levels (24).

The most direct method of controlling the charge applied to the skin is to use rectangular constant current pulses, in which the charge contained is a function of the current and pulse width (or duration) over which it is applied (I × W). The advantage of pulsed stimuli in contrast to sine wave stimuli is that the charge per pulse does not change with variations in repetition frequency (32).

Design of the electrode handset and cabling

In choosing a suitable metallic electrode material for use on the skin, limits are imposed due to physiological toxicity and mechanical strength. Two separate metallurgical problems exist, one being the necessary strength required of the electrode and connecting wire, and a second relating to electrolysis of electrodes in a fluid medium. Properties of the selected metal which are important will depend in the main on the particular application (33). In the case of the Tickle Talker, the electrodes must have robust mechanical and electrical stability, be biocompatible,

and able to pass adequate coulombic charge without electrolyzing tissue components. Although the mounting of the electrodes in the Tickle Talker handset is "dry," in that no electrolyte material is introduced to reduce skin electrical impedance, studies of dry electrode applications have indicated that small amounts of sweat accumulate quite rapidly on the skin surface under the electrode, and that for the purpose of establishing electrical contact with the skin, sweat is considered as a weak saline solution (34,35).

Metals chosen for electrodes include noble metals such as platinum, activated iridium, and activated rhodium, and non-noble metals such as stainless steel, titanium, zirconium, and tantalum. Stainless steel is ideal for strength, although it may not be completely corrosion-resistant. In the case of monopolar electrical stimulation, it is necessary to use a more stable material such as platinum (i.e., resistant to electrolysis), while still having sufficient mechanical strength and good electrical conductivity. Use of bipolar current pulses has already been stressed as important in the limiting of possible electrolysis (21), and this stimulus waveform has been used in the design of the Tickle Talker. Electrodes used in a stimulation situation also differ from those used for recording in that they must operate at much higher current densities. Studies of electrode materials have shown that the current-carrying capabilities of stainless steel and platinum are intermediate, being less than for rhodium, but superior to copper or aluminum (36). In the design of the Tickle Talker handset, both stainless steel and platinum electrodes have been used successfully.

Selection of materials for the wrist ground electrode was based on consideration of electrical conductivity and biocompatibility. The use of a smaller active and larger indifferent electrode results in much higher current density under the active electrode, causing the stimulus effect to be localized in the vicinity of the active electrode (21). Previous studies of electrocutaneous stimulation have reported the possibility of "sudden stings," resulting from a breakdown in the high electrical resistance of the skin (37). Detailed examination identified the existence of large numbers of current pathways in parallel under large surface area electrodes. The sudden sting experienced by some subjects was suggested as being due to a large portion of current being shunted through a single skin pathway in which the high resistance was broken down. This was found to become more prevalent with larger electrode surface area. In the case of the Tickle Talker, some sensations have been experienced at the wrist electrode, possibly due to a similar breakdown in the high resistance which normally allows the current to be spread over multiple pathways. This may be the result of uneven contact between the larger return electrode and the skin, creating higher electrical conductivity at one particular point under the electrode, and reducing the effective area difference between the active and indifferent electrodes. This in turn could result in similar current densities under both electrodes, producing sensations at the wrist electrode. Wrist stimulation effects have been relatively infrequent, and have usually been eliminated by repositioning of the wrist electrode. The relatively high resistance of the conductive rubber electrode, as compared to metal, and the better contact area achieved due to its flexible construction, may also limit the potential for dielectric breakdown effects. Two subjects have also reported some transient contact allergic reaction to the particular rubber used in the electrode. This situation was corrected by substituting an alternative rubber electrode material. A long-term solution, the elimination of the indifferent wrist electrode, has been implemented in the present device. In this case, the seven "inactive" electrodes are connected together and used instead of the wrist electrode.

Locally generated heat due to electrical stimulation has been suggested as a potential problem, especially when electrodes are used on dry skin (38). Previous studies have shown that tissue heating effects are minimized as separation between the positive and negative phases of biphasic pulses approaches zero, since the energy stored in the skin capacitance by the first phase is removed by the second, instead of being discharged through skin resistance, thus creating heat (32). The Tickle Talker uses a relatively short 100 μs gap between pulses that was introduced to increase the efficiency of the electrical stimulus pulses (20).

Stimulator/interface electrical circuit design

Assessments of potential risks inherent in the electrical design of the device included evaluation of the speech processor/stimulator circuitry, programming system, electrode handset and associated cabling. Electrical risk assessments were conducted for laboratory situations in which the device was attached to a mains-powered computer (i.e., during programming of the speech processor), and also for everyday situations in which the device was used as a wearable battery-powered speech processor. Independent biomedical engineering safety analyses of the first-generation prototype were also obtained from the Commonwealth of Australia, Department of Veterans' Affairs, and Department of Health, Medical Devices and Dental Products Branch.

Potential risks assessed included: accidental electric shock through breakdown of mains-powered equipment

(laboratory), accidental overstimulation through breakdown of the speech processor circuitry (wearable device), accidental overstimulation through breakdown of the stimulator circuitry, and accidental overstimulation through misuse.

Design considerations incorporated into the device to eliminate or reduce potential risks included the following:

Breakdown of Mains Equipment or Speech Processor Circuitry

The computer was powered through a mains isolation transformer, and the stimulator was electrically isolated from the speech processor circuitry through an opto-isolation linkage. Each of the electrodes in contact with the skin of the subject was connected to capacitors in series, thus limiting the possibility of DC current leakage between the subject and other equipment. In addition, a fused interface unit was included in the computer programming system to prevent passage of large current spikes to the equipment of the user while connected to the computer. The speech processor circuitry was waterproofed.

Breakdown of Stimulator Circuitry

The stimulator circuitry was designed such that failure of any one component could not result in accidental overstimulation. Capacitors were linked in series to the electrode outputs to provide protection against DC current flow from the stimulator unit. The stimulator was powered by a single 1.5 V AA cell, from which a +5 V supply, regulated by an integrated circuit voltage regulator was derived. In the first prototype, a +100 V stimulator supply was derived from a parallel-fed Cockcroft-Walton voltage multiplier. The voltage multiplier was driven from a square wave oscillator, which generated two outputs 180 degrees apart in phase. The frequency of operation and the component values were selected so that the high voltage would collapse if a sustained load was applied to the output through failure of the other components. In the second-generation prototype, where the speech processor and stimulator circuitry were incorporated into a single package, the 100 V supply was produced by a switching power supply. The output impedance of the 100 V supply was still sufficiently high for the voltage to fall to approximately 12 V within a few ms if a low impedance was placed continuously across the output. The DC current for a 1,000 ohm resistance would therefore be about 12 mA, which is still within accepted safe levels for electrocutaneous stimulation. The 1.5 mA output current was controlled by a field-effect transistor (FET) which functioned as a current-limiter. In addition, a constant current-limiting diode was fitted to the output of the stimulator unit. All internal components were functionally insulated where possible, and waterproofing was applied to the entire power supply and the electrode handset cable connections.

Operator Error or Misuse

Maximum pulse width was limited to 1,000 μs through the computer interfacing program. Increase in levels during setting of T and C pulse widths was controlled by the subject through an intensity control knob. Subjects were instructed prior to the setting of the C pulse widths to choose a level which would feel comfortable for continuous stimulation, rather than a level which verged on discomfort. Accidental supra-C-width stimulus pulses could be produced by overzealous turning of the intensity control knob. While this might prove uncomfortable, no tissue damage would occur due to the current limiting described previously.

The device was housed in a strong plastic case, with protective covers over access screws, and connections protected from mechanical hazards. No breakage of the plastic units has occurred. The microphone cable was encased in a flexible plastic sheath and was electrically shielded. The cable from speech processor/stimulator to handse· was constructed with a tough flexible plastic outer coating and a braided metal internal electrical shield, thereby providing protection for the internal wires.

Independent biomedical engineering analyses stated that the first-generation Tickle Talker met requirements of Australian Standard AS3200 (Electromedical Equipment) as a Class III device, which is the most intrinsically safe category of equipment (i.e., extra-low voltage powered). With that device, input signals from the outside world were transmitted into it via an isolation transformer, maintaining isolation of the user circuit from any earth-referenced source. The user circuit was further isolated by capacitive coupling, preventing leakage of DC currents to the user. In the present generation Tickle Talker, the isolation transformer has been replaced by opto-couplers.

SAFETY CONSIDERATIONS IN LONG-TERM DEVICE USE

Seven normally-hearing and four hearing-impaired adult subjects participated in the safety studies. The normally-hearing subjects were all university students and were paid for their participation. The four hearing-impaired subjects had been referred from the cochlear implant program at the University of Melbourne after failing to meet selection criteria for implantation. The safety studies were conducted concurrently with laboratory and field evalua—

Table 1.
Index finger temperatures for six normally-hearing subjects measured pre- and post-electrotactile stimulation for both stimulated (St) and unstimulated (NSt) index fingers.

		Temperature (°C)					
		Pre-Stim		Post-Stim		Pre/Post Diff	
Subject	Trial	St	NSt	St	NSt	St	NSt
1	1	35	35	33	33	−2	−2
	2	35	35	35	35	0	0
2	1	22.5	23	22.5	23	0	0
	2	23	23	21	23	−2	0
3	1	22	23	26.5	30	+4.5	+7
	2	35	35	35	34	0	−1
4	1	36.5	36	28	28.5	−8.5	−7.5
	2	35	34	28	29	−7	−5
5	1	35	35	32	33	−3	−2
	2	33	33	31.5	31	−1.5	−2
6	1	35.5	35	34 5	33.5	−1	−1.5
	2	28.5	30	26	28	−2.5	−2
Mean		31.3	31.4	29.4	30.1	−1.9	−1.3

+ denotes an increase in finger temperature post-stimulation, − denotes a decrease in finger temperature.

tion of the prototype device as a speech perception aid with the same subjects (22). As part of this training and evaluation program, the seven normally-hearing subjects received 70 hours of clinical training with the electrotactile device over a 6-month period. The hearing-impaired adults received 40 hours of clinical training (over 6 months), plus varying amounts of everyday use during the last 2 months of the training period. Subjects were free to choose not to participate in particular sections of the safety studies. In addition, two hearing-impaired adults who use the device as an everyday aid were assessed on a continuous basis over a 2-year period.

Study 1: Effects on local tissue: Finger temperature

Initial studies with the device found that skin temperature of the fingers in some individuals decreased by up to 3 degrees C following 30 minutes of electrotactile stimulation (20). These results suggested that the electrical stimulation was associated with some degree of vasoconstriction. Because of the potential implications of this as a side effect of the stimulus procedure, Study 1 was undertaken to quantify the prevalence and degree of skin cooling associated with longer-term use of the device.

Procedure

Finger temperature was measured for both the stimulated and nonstimulated index fingers for six normally-hearing subjects following completion of the 70-hour training and evaluation program. During the test session, temperature of the stimulated index finger was measured continuously with Yellow Springs Instruments (YSI-409 clinical thermometer and YSI-409A temperature probe). Initial recordings were made for 10 minutes with no stimulation to establish baselines for both stimulated and nonstimulated index fingers. Subsequently, 50 minutes of electrotactile stimulation was presented through the Tickle Talker, during which finger temperature of the stimulated index finger was continuously monitored. At the end of this period, temperature of the nonstimulated index finger was again measured. Trials were conducted on two different days for each of the six subjects. Input to the speech processor consisted of continuous speech prerecorded on audiocassette, and directly coupled to the input jack of the speech processor.

Results

Finger temperatures for the six normally-hearing subjects are shown in **Table 1**. Large variations in intersubject results are evident. In 8 of the 12 trials, cooling effects of 2.5 degrees C or less were found. Subject 4 (both trials) shows larger cooling effects of between 5.0 to 8.5 degrees C for both the stimulated and nonstimulated finger when post-stimulation temperatures are compared with pre-stimulation. In contrast, Subject 3 showed a post-stimulation warming effect on trial 1, for both the stimulated finger (4.5 degrees C) and nonstimulated finger (7.0 degrees C).

Since the temperature differences were not normally distributed, a Wilcoxon Matched-Pairs Signed Ranks Test was applied to the data. Comparison of stimulated index finger mean temperature with mean temperature of the unstimulated index finger prior to electrotactile stimulation showed a difference of 0.1 degrees C. Following electrotactile stimulation, the difference in mean temperature between the stimulated and nonstimulated index fingers had increased, with the stimulated index fingers showing a mean temperature 0.7 degrees C cooler than the nonstimulated fingers. However, results of the Wilcoxon Test showed that the differences in skin temperature

between the stimulated and unstimulated index fingers were not significant ($p > 0.05$), either prior to (T=8.5, p=0.667) or following electrotactile stimulation (T=13, p=0.142).

Comparison of mean temperatures from the pre-stimulation period with the post-stimulation period showed a cooling effect of −1.9 degrees C for the stimulated index fingers, and −1.3 degrees C for the nonstimulated fingers. Results of the Wilcoxon Test showed that these pre/post-stimulation differences were not significant ($p > 0.05$), for either the stimulated index finger (T=7, p=0.066), or non-stimulated finger (T=8, p=0.088).

Discussion

Although large inter- and intrasubject variability was evident, comparison of pre- and post-stimulation temperatures did not show a significant cooling effect for either the stimulated or nonstimulated index fingers in the group of subjects tested. Most subjects showed cooling effects of less than two degrees, well within the range of normal everyday fluctuations. However, Subject 4 showed a greater cooling effect in both hands on both trials. Closer examination of the calculated Wilcoxon test statistics for the pre- versus post-stimulation comparisons suggests the presence of a marginally significant cooling effect, especially in the case of the stimulated index finger, if a lower confidence level was accepted. Since our main concern was to limit the possibility of a Type II error (i.e., accepting that no cooling effect existed, when in fact it does), it would be appropriate in this case to accept a higher level of statistical significance. The possibility that some individuals (e.g., Subject 4) might be particularly susceptible to the effect must also be considered.

The most likely explanation for the observed cooling is vasoconstriction of unknown etiology, resulting in reduced blood flow to the skin surface. Because similar degrees of cooling were recorded for both the stimulated and unstimulated fingers in affected individuals, the possibility of sympathetic reflexive action must be considered. An increase in sympathetic reflexive activity could also result in elevation of mean arterial pressure and heart rate in affected individuals. Given the results of the statistical tests, the large cooling effects noted in some subjects, and the possible long-term side effects if sympathetic reflex activity was involved, a more detailed study to clarify the prevalence and causative factors of the observed finger cooling was considered necessary.

Study 2: Effect on local tissue: Vascular circulation

The goal of Study 2 was to quantify the degree of any vasoconstrictive effects in the fingers and hand under more controlled conditions, and clarify causative factors for any observed vasoconstriction in individual subjects.

Procedure

Five normally-hearing subjects participated in the vascular study. Subjects were screened for a history of cold intolerance or Raynaud's phenomenon, presence of cardiac arrhythmias, implanted pacemakers, or previous epileptic episodes. None of the subjects in the study were found to exhibit any of these conditions.

Analysis of vascular circulation in the hand and fingers of each subject was conducted after 3 months of training with the electrotactile device. Several measures were performed: 1) hand blood flow, measured by water plethysmography, at ambient hand temperatures of 20 degrees C and 40 degrees C, after body heating to abolish cutaneous sympathetic activity, and after the cold pressor test induced by placement of ice on the neck; 2) finger blood flow, measured by strain gauge plethysmography, at temperatures of 20 degrees C and 40 degrees C, and after body heating; and, 3) heart rate and blood pressure measured using a Dynamap™ automatic recording device.

All procedures were conducted in a controlled laboratory environment with an air temperature of approximately 23 degrees C. Subjects were recumbent for all procedures. The hand wearing the electrotactile device was placed in a water-filled plethysmograph at a level slightly above the right atrium, and a sphygmomanometer cuff, which could be inflated and deflated by an automatic device, was placed around the wrist. A cuff connected to a Dynamap automatic blood pressure recording device was placed on the contralateral arm. Hand blood flow (HBF) was measured at plethysmograph temperatures of 20 degrees C and 40 degrees C. After recording of the resting HBF measurements, a cold pressor test was performed at each plethysmograph temperature by placing a cube of ice on the neck for 10 seconds before inflation and 50 seconds after inflation. Body temperature was then raised by placing the subject between two electric blankets—a Space Blanket™ on top, and a second blanket wrapped around the head to prevent heat loss. Heating was continued until oral temperature had risen by 1 degree C or until frank sweating was evident. HBF was again measured at a plethysmograph temperature of 40 degrees C, and the cold pressor test repeated.

After measurement of each of these parameters in the pre-stimulation condition, the effects of electrotactile stimulation on the parameter were recorded. Input to the Tickle Talker consisted of continuous speech prerecorded on audiocassette and directly coupled to the input socket of the device.

Table 2.
Hand blood flow measured at plethysmograph temperatures of 20°C and 40°C, and after body heating, at rest and during the cold pressor test, prior to and during electrotactile stimulation.

	20°C		40°C		Body Heating	
Subject	Pre	Stim	Pre	Stim	Pre	Stim
Rest						
1	1.6	1.5	12.5	10.7	23.2	26.9
2	3.4	3.5	15.8	13.2	46.5	40.5
3	2.7	2.0	11.7	11.9	41.5	38.2
4	2.1	1.8	14.0	12.9	32.1	34.9
5	1.3	1.4	9.3	10.2	25.6	20.2
Mean	2.22	2.04	12.84	11.78	33.78	32.14
Cold Pressor						
1	0.5	0.6	4.7	4.9	14.0	11.2
2	1.3	1.6	6.3	7.8	16.2	15.0
3	1.8	1.1	3.8	1.4	18.3	19.1
4	0.4	0.2	6.8	3.3	18.1	16.2
5	0.4	0.8	3.6	2.7	11.2	10.3
Mean	0.98	0.86	5.04	4.02	15.56	14.36

All values are in ml/100ml/min.

Results

Table 2 shows results for measurements of HBF in ml/100ml/min, recorded both prior to and during electrotactile stimulation for three different temperature environments, and during the cold pressor test.

In all five subjects, HBF increased with increasing plethysmograph temperature. Addition of body heating (with the plethysmograph maintained at 40 degrees C) resulted in a further marked increase in flow. Following application of electrotactile stimulation, there was a small reduction in mean HBF for all three temperature environments. However, large inter- and intrasubject variations are evident in the data. Results of three-way analysis of variance (ANOVA) with temperature environment, presence/absence of electrotactile stimulation, and resting or cold pressor test as main factors showed no significant differences between mean HBF during absence or presence of electrotactile stimulation ($F^{(1,48)}$=0.6407, NS at $p>0.05$). However, results showed a significant difference in mean HBF measured across the three temperature environments ($F^{(2,48)}$=149.05, $p<0.001$). Post-hoc analysis using the Neumann-Keuls procedure showed that the means for the three temperature environments were significantly different ($p<0.05$), with a rank order of 20 degrees C < 40 degrees C < body heating.

In all subjects, application of the cold pressor test resulted in an immediate reduction in HBF, both prior to and during electrotactile stimulation, and in all three temperature environments ($F^{(1,48)}$=68.51, $p<0.001$).

Table 3 shows the ratio of HBF during the cold pressor test expressed as a percentage of preceding resting flow both prior to and during electrotactile stimulation for the five subjects. The ratios of reduction were relatively consistent between conditions and temperatures. Results of two-way ANOVA with absence/presence of electrotactile stimulation and temperature environment as main factors showed no significant differences in the cold pressor HBF ratios for either stimulus condition ($F^{(1,24)}$=0.431, NS $p>0.05$) or temperature environment ($F^{(2,24)}$=1.22, NS $p>0.05$).

Table 4 shows finger blood flow (FBF) (ml/100ml/min) measured prior to and during electrotactile stimulation in the three temperature environments. As shown, there was a slight reduction in FBF at all three temperatures tested, with mean FBF varying to a larger degree in the higher temperature environments. Two-way ANOVA did not show any significant difference in mean FBF for stimulation condition ($F^{(1,24)}$=1.07, NS $p>0.05$). However, large inter- and intrasubject variations were evident. Two-way ANOVA did show a significant effect of temperature environment on finger blood flow levels ($F^{(2,24)}$ = 109.19, $p<0.001$). Post-hoc comparison using the Neumann-Keuls procedure showed that each of the three temperature environment means were significantly different ($p<0.05$), with the same rank order as for HBF.

Table 4 also shows mean arterial pressure (MAP, in mmHg) and heart rate (HR, in beats/min) measured prior to and during electrotactile stimulation in all three temperature environments. As shown, mean MAP decreased slightly during body heating, both prior to and during electrotactile stimulation. Results of two-way analysis of

Table 3.
Hand blood flow during the cold pressor test as a percentage of preceding resting flow at plethysmograph temperatures of 20°C and 40°C, and after body heating both prior to and during electrotactile stimulation.

	20°C		40°C		Body Heating	
	Pre-Stim	Stim	Pre-Stim	Stim	Pre-Stim	Stim
Mean	44.8	41.8	38.9	33.7	47.9	45.2

All values are in percent.

Table 4.
Finger blood flow (FBF), mean arterial pressure (MAP), and heart rate (HR) measured at plethysmograph temperatures of 20°C and 40°C, and after body heating, prior to and during.

	20°C		40°C		Body Heating	
Test/Subject	Pre-Stim	Stim	Pre-Stim	Stim	Pre-Stim	Stim
FBF						
1	3.6	3.4	20.9	16.4	28.9	33.2
2	5.8	6.1	25.7	22.7	48.3	39.6
3	4.2	3.7	26.2	26.5	44.2	40.3
4	4.3	4.0	23.8	21.7	39.6	37.3
5	2.9	2.8	16.4	15.8	31.2	25.1
Mean	4.16	4.0	22.6	20.6	38.4	35.1
MAP						
1	80	80	78	79	74	73
2	76	76	74	73	73	74
3	85	85	85	88	80	80
4	84	85	83	86	80	75
5	82	83	80	79	79	83
Mean	81.4	81.8	80	81	77.4	77
HR						
1	68	69	71	73	89	87
2	66	65	69	69	92	95
3	64	64	65	69	84	82
4	67	70	72	73	89	92
5	67	69	69	68	76	79
Mean	66.4	67.4	69.2	70.4	86	87

Finger blood flow values are in ml/100ml/min, mean arterial pressure in mmHg, and heart rate in beats/min.

variance showed no significant effect on MAP for either stimulus condition ($F^{(1,24)}$=0.044, NS $p>0.05$) or temperature environment ($F^{(2,24)}$=2.752, NS $p>0.05$). During body heating, there was an increase in HR, for both stimulation conditions. Results of two-way ANOVA showed that although there was no effect of stimulus condition on HR ($F^{(1,24)}$=0.480, NS $p>0.05$), a significant effect was found for temperature environment ($F^{(2,24)}$=62.99, $p<0.001$). Post-hoc comparison using the Neumann-Keuls procedure showed that mean HR was significantly increased ($p<0.05$) after body heating.

Discussion

Previous studies (20) and Study 1 reported that electrotactile stimulation was associated with some degree of cooling of the skin of the fingers in some individuals. Reduction in HBF or FBF as a result of vasoconstriction was suggested as a potential reason for the observed cooling. Although results of the vascular study failed to demonstrate a significant group reduction in HBF or FBF during electrotactile stimulation, some individuals did evidence a minimal reduction. This vasoconstriction might be mediated by a number of mechanisms including: 1) direct excitation of sympathetic efferent nerve fibers; 2) stimulation of large somatic afferent fibers resulting in reflex vasoconstriction; 3) psychophysiological effects such as those shown in intense concentration; 4) changes in the relative ratio of blood flow between the arteriovenous anastomoses and nutritive capillary beds; or, 5) the stimulation might produce effects by mechanisms similar to those of "vibratory stimulation" as observed in vibration-induced white finger disease or Raynaud's disease.

Direct excitation of sympathetic efferent fibers is unlikely because the vasoconstriction effects reported in individuals in Study 1 were not confined to the fingers on which stimulation occurred. No sweating, increase in heart rate, or MAP was evident in Study 2 following electrotactile stimulation, as would be expected from direct stimulation of sympathetics. Threshold for postganglionic sympathetic efferents should also be substantially higher than for the larger myelinated touch/proprioceptive afferents, and in the same range as pain fibers. Therefore, stimuli adjusted for the touch afferents should be subthreshold for the sympathetic efferents. In addition, in Study 2, cooling effects during electrotactile stimulation were noted by some individuals following body heating, which should have effectively abolished all sympathetic activity.

Transient vasoconstriction may be caused by any skin sensory stimulus: however, a repetitive touch stimulus would be unlikely to cause a sustained reflex vasoconstriction due to habituation effects (39). Vasoconstriction mediated by reflex effects could affect the contralateral hand, and the results of Study 1 did suggest cooling in both hands of affected subjects.

Psychophysiological effects such as those associated with mental arithmetic can cause quite sustained symmetrical vasoconstriction in the hands, usually associated with a rise in heart rate and blood pressure. Reductions in HBF from 3.3 to 2.9ml/100ml/min in cold, and from 14.4 to 8.7ml/100ml/min in warm conditions have been noted, together with increases in heart rate and MAP, indicating a marked increase in resistance to blood flow (39). While this might be a plausible explanation since intense concentration is required when using the device for supplementation of lipreading, subjects in Study 1 showed cooling of

both hands, even though no concentration task was required and no increase in MAP or HR were evidenced during application of electrotactile stimulation in Study 2.

Pathological effects such as those associated with Raynaud's phenomenon or disease could be a potential explanation for the observed vasoconstriction noted. This cooling phenomenon, usually associated with hazards of vibrating tools, has several different theories as to causative factors. These include the sensitization of the arteries to noradrenalin as a result of mechanical vibration (40), or reflex effects originating from the pacinian corpuscles (41). However, one would expect to see enhanced vasoconstrictor response to local cooling at plethysmograph temperatures of 20 degrees C, which was not evidenced in the cold pressor results across temperature environment. In addition, there was no evidence of structural changes during presence of electrotactile stimulation since HBF at maximal vasodilation during body heating was not significantly different from HBF in the pre-stimulation condition.

In summary, sympathetic efferent and pathological causes for the observed cooling and vasoconstriction noted in some individuals can be eliminated as contributing factors. The most likely explanation is that the electrotactile stimulation is altering some baseline condition in arteriovenous anastomoses, resulting in changes in the ratio of blood flow between the arteriovenous anastomoses and nutritive capillary beds. However, it must be stressed that no significant group effect was detected, and that the degree of reduction in HBF or FBF, or finger temperature cooling noted for individuals in Studies 1 and 2 was minimal, and should not be seen as a general limiting factor in the use of the device. It is suggested that potential users of the Tickle Talker be screened for the presence of any scleroderma or white finger disease prior to using the device.

Study 3: Effects on peripheral nervous system: T/C pulse widths

Initial studies with the Tickle Talker reported that threshold (T) and maximum comfortable (C) pulse widths selected by subjects showed some increase over time (20). Since a possible explanation for a rise in electrical thresholds could be due to physiological changes in tissue or nerve function, Study 3 aimed to quantify the prevalence and degree of any observed changes in T and C pulse widths following longer-term experience with electrotactile stimulation.

Procedure

Mean T and C pulse width levels for the eight electrodes were recorded for the seven normally-hearing subjects over the 6-month training period. The actual number of sessions recorded varied slightly between subjects, most notably in the case of Subject 3, who showed a marked change in T and C pulse widths following the introduction of a modified electrode geometry. Due to this change, additional measurements were made on this subject. Mean T and C pulse widths were also measured over time for five hearing-impaired adults using the device as an everyday aid. The number of recording sessions and the period over which the measurements were made varied from 6 to 36 months.

Subsequently, for GM and JC, who had received 24 and 36 months of training and experience with the device respectively, mean T and C pulse widths for the eight elec-

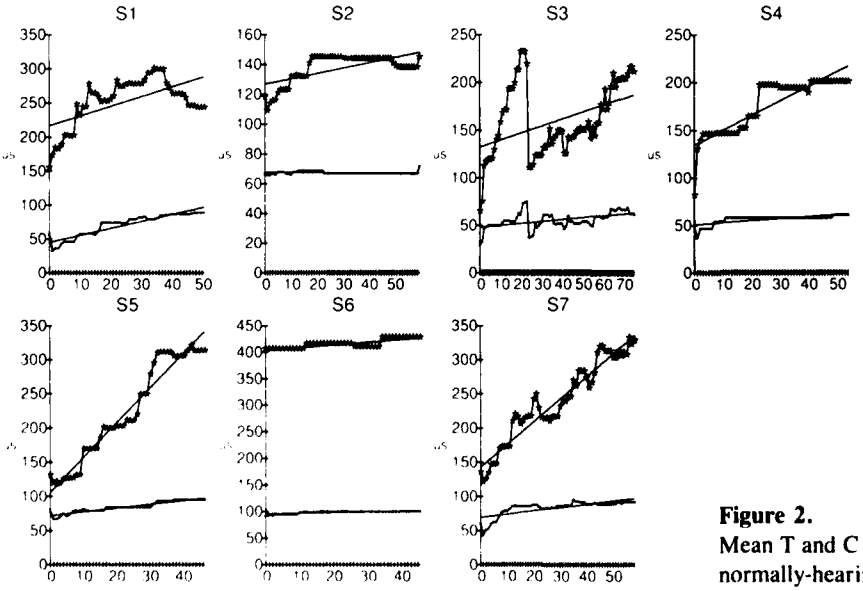

Figure 2.
Mean T and C pulse widths (eight electrodes in μs/session) for seven normally-hearing subjects measured over a 6-month period.

Table 5.
Statistical data for regression line analysis of mean threshold (T) and comfortable (C) pulse widths for seven normally-hearing and five hearing-impaired adult subjects.

Subject	n (sessions)	Time (months)	Level	Corr.Coeff. (μ/session)	Slope *a* (μ/month)	*t*-stat. *a*	Slope *c*
1	50	6	T	0.933	1.037	18.106	8.642
			C	0.604	1.435	5.299	11.958
2	59	6	T	−0.092	−0.005	−0.705	−0.049
			C	0.647	0.359	6.455	3.530
3	75	6	T	0.519	0.206	5.228	2.575
			C	0.429	0.729	4.079	9.113
4	54	6	T	0.710	0.028	7.346	0.252
			C	0.886	1.534	13.883	13.806
5	46	6	T	0.941	0.554	18.596	4.247
			C	0.974	5.146	28.631	39.452
6	45	6	T	0.774	0.134	8.097	1.005
			C	0.815	0.512	9.319	3.84
7	58	6	T	0.747	0.487	8.483	4.701
			C	0.962	3.335	26.665	32.238
JC	89	36	T	0.704	0.735	9.308	1.817
			C	0.904	2.973	19.787	7.349
PL	56	12	T	0.931	1.600	18.833	7.467
			C	0.874	5.374	13.322	25.079
PB	47	12	T	0.278	0.094	1.959	0.368
			C	0.149	0.144	1.022	0.564
SS	22	6	T	0.425	0.195	2.152	0.715
			C	0.923	3.284	10.952	12.04
GM	54	24	T	−0.459	−1.237	−3.765	−2.78
			C	−0.625	−4.952	−5.823	−11.14

Slope *a* is uncorrected slope of regression lines shown in Figures 2 and 3; *t*-stat. *a* is confidence interval on that slope; slope *c* is slope of regression line corrected for number of months over which session measurements were taken.

trodes on the stimulated hand were compared with pulse widths measured on the hand which had not previously received electrotactile stimulation. Similar measurements of stimulated and nonstimulated hand mean T and C pulse widths were made for three normally-hearing members of the research staff with long-term exposure to electrotactile stimulation provided through the device.

Results

Figure 2 shows mean T and C pulse widths for eight

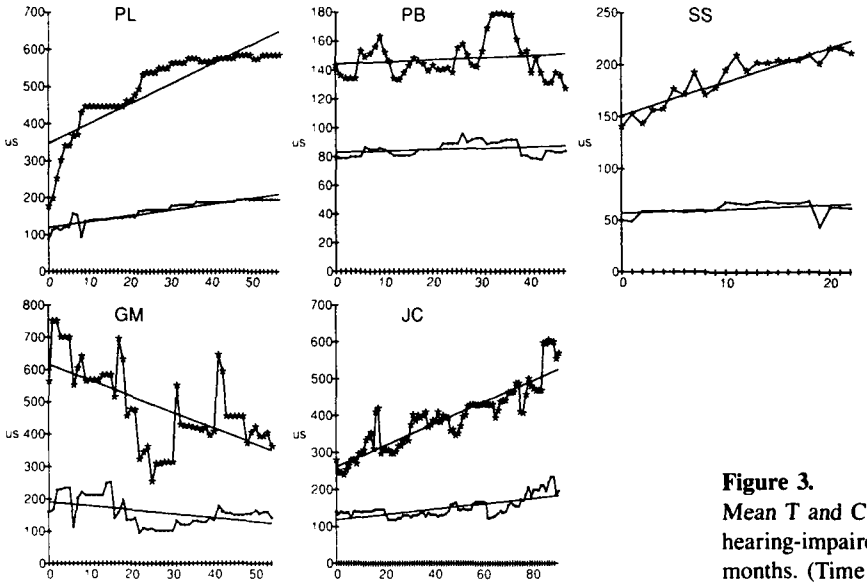

Figure 3.
Mean T and C pulse widths (eight electrodes in μs/session) for five hearing-impaired adults measured over periods ranging from 6 to 36 months. (Time periods for individual subjects are given in **Table 5**).

electrodes recorded over the 6-month period for the seven normally-hearing subjects (Subject 1-Subject 7). Visual inspection of the graphs shows variation in mean T pulse widths over this period to be less than for C pulse widths for all subjects. Overall, mean T pulse widths show little increase over the recording period, while changes in mean C pulse widths vary between subjects.

Results of statistical analysis, shown as **Table 5**, indicate a significant increase in mean T and C pulse widths over time (i.e., significant upward slope of the best fit regression line $p<0.05$), for all normally-hearing subjects except Subject 2 (T pulse widths only). As shown, slope of the regression line (in μs/session) was greater for mean C pulse widths than for mean T pulse widths for all of the subjects. As the number of sessions varied slightly between subjects, a corrected slope value (in μs/month) was calculated to allow more accurate comparison of changes over time, and these values are also shown in **Table 5**. This was calculated according to the formula:

$$\text{corrected slope } c = \frac{\text{slope } a \times \text{number of sessions}}{\text{number of months training}}$$

Corrected slopes for mean T pulse widths showed changes from −0.049 to 8.64 μs/month, while changes in mean C pulse widths ranged from 3.53 to 39.45 μs/month, confirming the visual observations that changes in mean T pulse widths were less than for mean C pulse widths.

Similar data for five hearing-impaired adults is shown in **Figure 3** and **Table 5**. Variations in mean C pulse widths were greater than for mean thresholds, and significant increases in both T and C pulse widths were measured over varied time periods for all subjects except PB (both T and C), SS (T only), and GM (both T and C). In four of the adults (PL, PB, SS, JC) slope of the mean C pulse width regression lines (in μs/session) were much greater than for mean thresholds. Comparison of changes in corrected slope measured in μs/month for these four adults shows a range of 0.368 to 7.467 μs/month for mean T pulse widths, and 0.564 to 25.079 μs/month for mean C pulse widths. These values are similar to those recorded for the normally-hearing subjects.

Mean T and C pulse widths recorded for hearing-impaired subject GM, who has participated in training and used the device over a period of 2 years, show a different pattern of change from those of the other normally-hearing subjects and hearing-impaired adults, in that both mean T and C pulse widths decreased over time.

Table 6 shows a comparison of mean T and C pulse widths for the stimulated and nonstimulated hands for GM and JC, who had received respectively 24 and 36 months of training and experience, and for three normally-hearing adults (members of the research staff) with extensive electrotactile experience. Mean T and C pulse widths were similar in the stimulated and nonstimulated hands subsequent to extensive long-term experience with the device for all subjects except GM. Results of paired *t*-tests showed that the differences between mean pulse widths for the stimulated and nonstimulated fingers were not significant for either mean T pulse widths (t=2.54, df=4, NS $p>0.05$) or mean C pulse widths (t=1.24, df=4, NS $p>0.05$). GM,

Table 6.
Comparison of mean T and C pulse widths in the stimulated (St) and non-stimulated (NSt) hands for 2 hearing-impaired and 3 normally-hearing adults.

Subject	Mean T (μs) St	Mean T (μs) NSt	Mean C (μs) St	Mean C (μs) NSt
A	102	113	197	194
B	64	63	286	213
C	288	315	474	485
GM	118	127	429	235
JC	186	197	553	568
Mean difference St-NSt	−11.4		49	
p	NS, $p>0.05$		NS, $p>0.05$	

who shows lower mean C pulse widths in the nonstimulated finger, noted during testing that the intensities set for the nonstimulated hand were subjectively lower than for his normally-used hand. However, the unfamiliarity of the different sensations experienced proved uncomfortable to GM, and resulted in the setting of lower C pulse widths than those accepted for the normally-used left hand.

Discussion

T and C pulse widths for the eight electrodes may depend on a number of factors: 1) geometry of the electrode/skin interface; 2) electrode position relative to the nerve bundles; 3) subjective criteria used to set T and C levels; and, 4) sensitivity of nerve bundles to electrical current.

To a large extent, the first two factors could not be controlled in the experimental design, since exact positioning varied between sessions, and different electrode shapes and sizes were used throughout the study period for developmental reasons. Subjective criteria could also vary between sessions, especially as the users became experienced with the potential speech discrimination benefits available through use of the device. This would be expected in the case of the hearing-impaired adults, but the normally-hearing users were also quite enthusiastic about achieving the best connected discourse scores and overall performance. However, our main aim was to determine that there was no change in factor 4, the sensitivity of the nerve bundles to electrical current, through comparison of mean thresholds in the stimulated versus unstimulated hands after long-term use of the device.

Recordings of mean T and C pulse widths, following prolonged experience with the device, showed that significant increases in mean C pulse widths were evident for most subjects. Increases in mean C pulse widths were overall greater than for T pulse widths. JC and GM, who were evaluated over a longer period, showed marked fluctuations in pattern for mean T and C pulse widths. As discussed, these individual variations may reflect effects of different electrode designs, geometry of the electrode/skin interface, or placement of the electrodes in relation to the position of the digital nerve bundles. During this period, three different models of handset and electrode size were tested. Effects of electrode surface area are seen clearly for Subject 3, who was provided with a new handset with slightly larger surface area electrodes after session 20. In separate experiments, variations in both T and C mean pulse widths were found for electrodes differing in surface area, shape, and material of construction.

No significant differences were found between mean T and C pulse widths in the stimulated and nonstimulated hands for experienced long-term users of the device. This suggests that the increases shown were not due to physiological changes in the sensitivity of the digital nerve bundles in the stimulated hand as a result of exposure to electrotactile stimulation. The observed increase in mean C pulse widths may be due to changes in the subjective criterion used by particular users in setting of C pulse widths as a "most comfortable level" in contrast to a discomfort level. The increase shown over time may reflect subjective changes such as acceptance of stronger stimuli as the users become more familiar with the sensation and the potential benefits available from the device. This would be consistent with the findings of similar C pulse widths in both the stimulated and unstimulated hands of the experienced users.

In contrast to the other subjects, GM shows a progressive decrease in mean C pulse widths over time. In early work with GM, repeated explanations were required to ensure that C pulse widths were not set at discomfort levels to "ensure a clear signal." The decrease in mean C pulse widths for GM may reflect a more realistic subjective setting of pulse widths for long-term use of the device.

Overall, the results do not indicate any systematic change or habituation of mean T or C pulse width levels which would be consistent with changes in sensitivity of the digital nerve bundles in the stimulated hand subsequent to electrotactile stimulation presented through the Tickle Talker. However, long-term monitoring of mean T and C pulse widths will be continued with both children and adults using the Tickle Talker as an everyday speech perception aid.

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Study 4: Effects on peripheral nervous system: Tactual sensitivity

Study 4 examined the effects of longer-term exposure to electrotactile stimulation on tactual sensitivity in the fingers of the stimulated hand. In a similar methodology to the initial finger temperature recordings reported in Study 1, the tests were chosen for their simplicity and ease of application rather than as an in-depth analysis of tactual perception. A more detailed evaluation similar to that of Study 2 was planned if potentially significant effects which might limit long-term device use were suggested by the results of the initial measures.

Procedure

Three standard measures of tactual sensitivity were used: sharp-dull discrimination, hot-cold discrimination, and two-point difference limen. Measures were made on both the stimulated and nonstimulated index fingers for six normally-hearing subjects, subsequent to their completion of the training/evaluation program.

Sharp-dull distinctions were tested using alternate ends of a laboratory dissection pin as a stimulus. One end of the dissection pin was sharply pointed, while the opposite end was a flattened surface (2 mm^2). Ten random-order 1 sec presentations of both the sharp and dull stimulus were made to the index finger pad of both the stimulated and nonstimulated fingers.

Hot-cold sensitivity was measured in a similar manner, utilizing standard laboratory test tubes containing hot and cold water as stimuli. Ten random-order 1 sec presentations of the hot and cold stimuli were made to the finger pad of the distal phalanx of both the stimulated and nonstimulated index fingers.

Two-point sensitivity was measured on the finger pad of the distal phalanx. Either one or both points of a twin-point compass were pressed on the pad for a period of 0.5 sec, and subjects were asked to respond with the number of points felt. Micrometer adjustments were made to the distance between points, which was increased until the subject consistently reported the stimulus as containing two points.

For each of the three tactual sensitivity measures, the subjects' hands were excluded from their visual field, and no feedback on correctness of response was given. Stimuli were presented prior to and immediately following 50 minutes of continuous electrotactile stimulation. Two separate trials for each of the kinesthetic sensitivity measures were conducted on different days for each of the six subjects. Input to the Tickle Talker was continuous speech, prerecorded on audiocassette, and directly coupled to the input socket of the device.

Table 7.
Sharp-Dull and Hot-Cold discrimination scores for six normally-hearing subjects measured pre- and post-electrotactile stimulation for both stimulated (St) and unstimulated (NSt) index fingers.

		Correct Discriminations (×/10)							
		Sharp/Dull				Hot/Cold			
Subject	Trial	Pre-Stim		Post-Stim		Pre-Stim		Post-Stim	
		St	NSt	St	NSt	St	NSt	St	NSt
1	1	10	10	10	10	10	10	10	10
	2	10	10	10	10	10	10	9	9
2	1	10	10	10	9	10	10	10	10
	2	10	9	10	9	10	10	10	10
3	1	10	10	10	10	10	10	10	10
	2	10	10	10	10	10	10	10	10
4	1	9	10	10	10	10	10	10	9
	2	10	9	10	10	10	10	10	10
5	1	10	9	10	9	10	10	10	10
	2	10	10	10	10	10	10	10	10
6	1	10	10	10	10	10	10	10	10
	2	10	10	10	10	10	10	10	10

All values are in number of trials out of 10.

Results

Table 7 and **Table 8** show results for the three tactual sensitivity tests with the six normally-hearing subjects.

As shown in **Table 7**, no obvious differences in sharp-dull, or hot-cold sensitivity were evident either for comparison of pre-stimulation versus post-stimulation results, or for comparison of the stimulated versus unstimulated hand for any of the subjects.

Results for two-point discrimination limens (**Table 8**) are more variable. Mean two-point discrimination limens were reduced for both the stimulated (1.64 mm pre versus 1.43 mm post) and nonstimulated finger (1.6 mm pre versus 1.37 mm post) following the 50-minute electrotactile stimulus period. Results of paired *t*-tests indicated that the differences between pre- and post-stimulation means were not significant for either the stimulated ($t=-1.345$, $df=11$, NS $p>0.05$) or unstimulated index finger ($t=-2.02$, $df=11$, NS $p>0.05$). However, large intersubject variations were evident. For example, Subject 4 shows reductions in two-point limens post-stimulation for stimulated (both trials) and nonstimulated fingers (one trial), while Subjects 2 and 3 show

Table 8.
Two-point discrimination limens measured for six normally-hearing subjects pre- and post-electrotactile stimulation for stimulated (St) and unstimulated (NSt) index fingers.

		Two-point Discrimination Limen (mm)					
		Pre-Stim		Post-Stim		Pre/Post Diff	
Subject	Trial	St	NSt	St	NSt	St	NSt
1	1	2.2	2.2	2.1	2.0	−0.1	−0.2
	2	2.0	2.0	2.0	2.0	0	0
2	1	1.5	1.8	1.8	1.8	+0.3	0
	2	1.2	1.2	1.5	1.1	+0.3	−0.1
3	1	1.0	1.2	1.1	1.3	+0.1	+0.1
	2	1.1	1.6	1.5	1.5	+0.4	−0.1
4	1	2.5	2.0	1.0	1.0	−1.5	−1.0
	2	1.6	1.0	1.3	1.0	−0.3	0
5	1	1.5	1.5	1.1	0.9	−0.4	−0.6
	2	1.5	1.5	1.0	1.0	−0.5	−0.5
6	1	1.8	1.8	1.8	1.8	0	0
	2	1.8	1.4	1.0	1.0	−0.8	−0.4
Mean		1.64	1.6	1.43	1.37	−0.21	−0.23

A + for pre/post difference denotes an increase in two-point limen, while a − denotes a decrease; all values are in mm.

small increases in two-point difference limens in the stimulated finger post-stimulation. A *t*-test comparing mean two-point difference limens for the stimulated and non-stimulated index fingers following electrotactile stimulation did not find any significant difference (t=1.349, df=11, NS $p>0.05$).

Discussion

No significant changes were noted following electrotactile stimulation on either the sharp-dull or hot-cold tactual sensitivity measures. While a change was noted for some subjects on the two-point difference limen test, the mean effect was a reduction in difference limen, suggesting an increase in tactual sensitivity following electrotactile stimulation. This would not be consistent with any decrement in peripheral nerve function resulting from electrotactile stimulation.

Overall, the results of the three tactual sensitivity measures did not detect significant changes following electrotactile stimulation. While the tests are rather crude, it would be expected that any marked decrement in sensitivity resulting from electrotactile stimulation would be evident as a consistent pattern in the results. Given the findings, no further detailed study was considered necessary.

Study 5: Effects on central nervous system: EEG recordings

While it is unlikely that electrocutaneous stimulation would have detrimental effects on central nervous function, a factor relating to a specific hearing-impaired group who potentially might use the device necessitated an assessment. Many cases of early acquired severe-to-profound deafness are a result of meningitis. It is also well-known that meningitis and encephalitis are associated with an increased incidence of focal spike discharges and epilepsy (42,43). Recent reports suggest that epilepsy occurs in 2 to 3 percent of children who have had previous meningitis, as compared with the generally accepted prevalence of epilepsy in the community of 0.5 to 1.0 percent (44,45). Since epileptic episodes may result from repetitive external stimuli (e.g., photic stimuli), an examination of the effects of continuous electrotactile stimulation on electroencephalographic (EGG) recordings was undertaken to investigate the possibility that the electrical stimulation could act as an activator for focal discharges.

Procedures

Standard EEG recordings (46) were made in sessions prior to, during, and immediately following cessation of electrotactile stimulation of the digital nerves of the hand with output from the Tickle Talker. Seven normally-hearing and three hearing-impaired subjects participated in this study. As with the other studies, continuous speech input was prerecorded on audiocassettes, and presented through a Sony Walkman, which was directly coupled to the input socket on the Tickle Talker. EEGs were recorded while the subjects were resting, with eyes open, eyes closed, during hyperventilation, and with photic stimulation. Each recording was approximately 20 min long and made on a 16-channel EEG machine, utilizing from 10 to 20 Montage positions with bipolar, average reference, and source derivation recordings. Each of the seven normally-hearing subjects had three recording sessions, the first one prior to exposure to electrotactile stimulation, the second following 35 hours of training with the device, and a third following an additional 35 hours of training. Hearing-impaired subjects had two recording sessions, one prior to electrotactile training, and one following 40 hours of training in use of the device. As discussed, each of the hearing-impaired adults also used the processor for variable amounts of additional time as an everyday aid during this

Table 9.
Analysis of EEG recordings for seven normally-hearing and four hearing-impaired subjects prior to electrotactile training, and after three and six months electrotactile experience.

Session	Subject									
	1	2	3	4	5	6	7	JC	PB	PL
1st EEG	HV+	U	HV+	U	U	U	U	U	U	U
2nd EEG	HV+	U	HV+	HV+	U	U	U	U	U	U
3rd EEG	U	U	HV+	HV+	U	U	HV+			

U denotes unremarkable EEG, HV+ denotes slow and/or sharp wave forms with or just after hyperventilation.

period. EEG recordings were visually analyzed in a "blind" random order by an experienced neurophysician.

Results

Table 9 shows results of the analysis of EEG tracings for the seven normally-hearing and three hearing-impaired subjects.

Results shown with a "U" indicate an unremarkable EEG, while HV+ is used where there was a prominent build-up of slow and/or sharp wave forms during or just after hyperventilation. As shown, HV+ traces were found in two subjects at the first recording, in three subjects at the second, and in three subjects at the third. Subject 3 showed an HV+ trace at all three recordings. However, no consistent pattern of HV+ recordings was evident for the other subjects. No other difference or abnormality of EEG pattern was detected between successive EEG recordings.

Discussion

Results of the EEG study did not detect any systematic difference in recordings during or subsequent to electrotactile stimulation presented through the Tickle Talker. No paroxysmal activity of epileptic type, or other abnormality was evident in conjunction with the periods of electrotactile stimulation. The increase in slow or sharp waveforms associated with hyperventilation may reflect the vigor with which individual subjects performed hyperventilation. Activation of the electroencephalogram by hyperventilation arises as a result of the lowering of serum CO_2 levels during increased expiration. This consequently results in a more alkaline blood pH (47). Hypocapnia and alkalosis increases the excitability of the cortical cells, and epileptic foci and other disturbances may be more clearly manifested. In normal adults, EEG changes in response to hyperventilation are minimal. Young adults may show a nonparoxysmal slowing of the EEG and occurrence of bilateral sharp waves during the second or third minute of hyperventilation, which disappear within 20 to 30 sec of return to normal breathing (48). This is consistent with the results for hyperventilation shown by some of the subjects. However, these results do not suggest any consistent effect of the electrotactile stimulation on the EEG which might be construed as pathological, or predisposing to epileptic episodes.

DISCUSSION

The results indicate that the electrotactile stimulation provided through the Tickle Talker is safe for use. Analyses of the stimulus waveform, speech processor, and stimulator electric circuit layout, and handset/cabling design show that potential problems relevant to the electrical nature of the stimulus and device have been addressed, and that user safety has been ensured. Results of tactual, vascular, and neurological evaluations have shown no significant effects on local tissue, peripheral nervous system, or central nervous system function which might limit application of the device.

In addition to the data presented, 15 hearing-impaired children and 4 adults have now been using the device for periods of up to 3 years. Results show significant benefits in improving speech perception from use of the Tickle Talker for both children and adults (11,49). No biomedical or safety problems were encountered by either hearing-impaired adults or children using the Tickle Talker as an everyday aid after periods exceeding two and one-half years of use. Despite some transient problems with wrist stimulation which were resolved by elimination of the common wrist electrode, all users accepted the device as an everyday communication aid.

While these results are encouraging, longer-term safety studies with the device are continuing because the potential for problems to arise after several years of electrotactile stimulation must be examined. As discussed, tactile sensory devices have a lengthy history, apparently without incidence of serious biomedical complications (50). However, given that few devices have achieved acceptance and everyday use by large numbers of subjects over many years, the safety aspects cannot be guaranteed. While hearing-impaired adults and parents of hearing-impaired children may be adequately informed and accept the potential risks after weighing the potential benefits to speech

perception available through the use of a particular device, researchers and manufacturers have a clear responsibility to ensure the long-term safety of devices, especially those used by children. It is hoped that safety studies, similar to those conducted for cochlear prostheses and as reported in the present study, will become accepted practice for researchers involved in development of electrotactile and vibrotactile speech aids.

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Speech recognition performance on a modified nonsense syllable test

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Abstract—A modification of the City University of New York nonsense syllable test (CUNY NST) has been developed in which (*a*) the several subtests of the original test are replaced with a 22-item consonant-vowel (CV) subtest and a 16-item vowel-consonant (VC) subtest; and, (*b*) the response choices for each target syllable include all 22 initial and all 16 final consonants, respectively. In addition, the test tokens are presented as isolated syllables without a carrier phrase. These changes enable the resolution of confusions not possible on the original NST, and also the construction of a single confusion matrix each for CVs and VCs, respectively. The modified nonsense syllable test (MNST) provides results that compare favorably to those of the original NST.

Key words: *consonant confusions, hearing, nonsense syllables, speech discrimination, speech intelligibility, speech recognition.*

INTRODUCTION

The City University of New York (CUNY) Nonsense Syllable Test (NST) (1,2) is a closed-set speech recognition test involving the identification of consonants that are presented in a framework of meaningless consonant-vowel (CV) and vowel-consonant (VC) syllables. It was originally constructed to resolve performance differences and phoneme identification errors arising from the use of alternative hearing aid conditions. Since its introduction, the NST has been extensively documented acoustically and perceptually, and has been shown to be impressively precise and reliable (2,3,4,5). Consequently, the NST has been employed successfully in many studies dealing with both theoretical and clinical issues.

Because of its originally-intended application, the NST was designed to concentrate on the kinds of consonant confusion errors that are the *most likely* to occur (2). For this reason, the NST was constructed in the form of subtests (or subsets). Any given subset of the NST tests from seven to nine different consonants, and the possible response alternatives for a given nonsense syllable presented to the subject, are limited to the syllables in that particular subset. Specifically, the choices in a given subset include the target consonant itself and alternatives differing from the target sound in place and/or manner of articulation. Voicing confusions, however, are not included because they occur only infrequently.

As a result of this approach, the NST is able to reveal place and/or manner confusions with high resolution. On the other hand, it cannot resolve voicing errors—because these are not possible choices in the response frames—or other perceptual confusions for which the perceived consonants are not represented within the same subtest as the stimulus (6). Thus, it is conceivable that at least some measured perceptual confusions are not represented as they were heard because the perceived consonant was not among the possible choices. In addition, the results generated by the NST do not enable one to construct a single confusion matrix (one each for CVs and VCs, respectfully), because

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Table 1.
Alternatives per stimulus on the MNST in the orthographic form presented in alphabetical order for each stimulus item.*

Initial:	b ch d f g h j k l m n p r s sh t th TH v w y z
Final:	b d f g k m n ng p s sh t th TH v z

* Corresponding phonemes for the orthographic representations are: "ch" / tʃ /; "j" /dʒ/; "sh" /ʃ/; "th" (θ); "TH" (ð); "y" /j/; "ng" /ŋ/.
MNST = Modified Nonsense Syllable Test.

all possible responses are not permitted for all possible stimuli. Consequently, the usefulness of the test can be limited in situations where one is interested in a wide range of possible perceptual confusions, and/or when one confusion matrix is needed for the intended analysis.

This report describes a modification of the NST that was undertaken to overcome these limitations, while retaining the well-established overall integrity of the test. In addition, it presents initial speech recognition findings obtained with the modified test using normal hearing subjects.

METHOD

Modifications of the NST

Briefly, the modified NST was constructed as follows: Beginning with a submaster recording of the original NST (using a male talker), each CV and VC with vowel /a/ was low-pass filtered (at 10,000 Hz) and digitized (at a 25,000 Hz sample rate). The carrier phrase ("You will mark — please") was then extracted using a waveform editing program, leaving only the test syllable itself.

The carrier was omitted for two reasons. The first reason related to our principal intended use for the test in reverberation experiments. Here, we wanted to study the effects of reverberation upon the perception of the test syllables, *per se,* without contamination of the results due to temporal smearing from other utterances (i.e., the carrier phrase). The second reason was a pragmatic one—to minimize the already extensive testing time dictated by the large number of conditions and replications that typify the applications of such a test.

Each digitized nonsense syllable was then stored as an individual file. The digitally stored syllables were then randomized into test lists. Each randomized test list contained the identical tokens as any other list except, of course, that their order was different. Each initial consonant test list included 22 CVs, and each final consonant list included 16 VCs. After processing and randomization, the resulting syllable lists were recorded onto magnetic tape for testing purposes. For each stimulus token, the subjects were given a choice of all 22 CV alternatives for every syllable presented in the initial test, and with all 16 VC alternatives for each one presented in the final test. Subjects responded by marking the chosen response alternative on an answer sheet.

Table 1 shows the 22 items on the CV subtest, and the 16 tokens included in the VC subtest. These are shown orthographically in alphabetical order as on the answer sheets used by the subjects.[1]

EXPERIMENT I

Subjects

The subjects included 12 normal hearing adults who were native speakers of English with no history or complaints of neurologic or otologic problems. They included 10 females and two males ranging in age from 22 to 48 (mean 28) years. Each subject had pure tone thresholds not exceeding 10 dB HL (7) at 250-8000 Hz, and normal tympanograms and acoustic reflexes (8,9) for both ears.

Procedure

All testing was accomplished in a sound-treated room exceeding the American National Standards Institute (ANSI) S3.1 (1960), standard for audiometric environments (10). Following instructions and the administration of a practice list, the modified NST was presented to each subject monaurally through a TDH-50 earphone and supra-aural cushion at sound pressure levels (SPL) of 20, 28, 36, 44, and 52 dB. Presentation order was randomized among all of the conditions. Performance-intensity functions were obtained for the syllables presented alone (i.e., in quiet) and also in the presence of an equalized cafeteria babble at a S/N ratio of +5 dB. These levels and S/N ratios correspond to those previously reported for the original NST by Dubno and Levitt (5).

The subjects were tested individually in one or two sessions. Each subject received all of the conditions twice, and each score was based on the average of these two presentations.

[1]The process of scanning the many alternatives to choose and mark a response is an admittedly complex process for the subject. This appears to be an unavoidable problem when using tests of this type. In order to avoid errors in this study, the tester constantly monitored the stimuli and the subject's responses to assure that the subject was keeping up with the test; and the tape was stopped and/or items were repeated, as necessary. Experience suggested that keeping up with the test was not difficult for our young, normal subjects except at lowest levels where the material was barely audible.

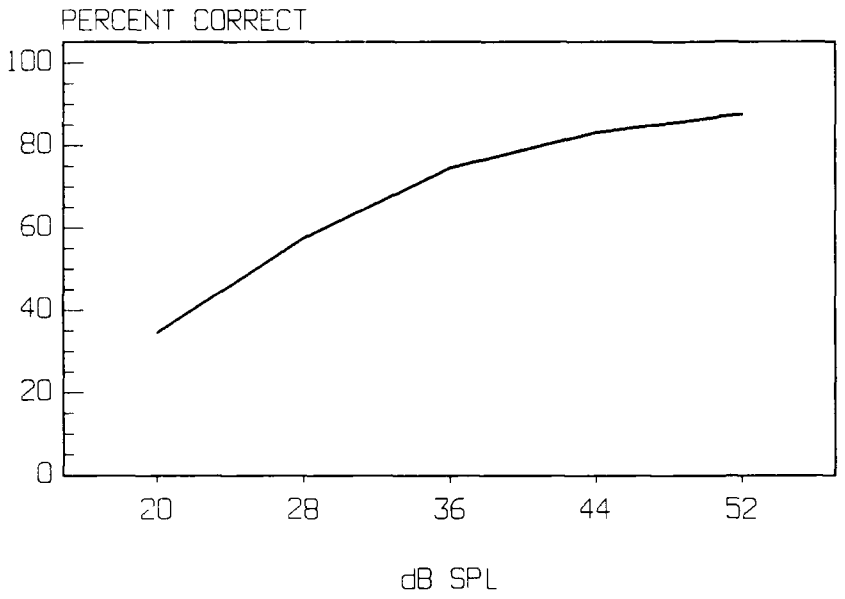

Figure 1.
Performance-intensity function for overall percent correct performance on the MNST combined across all conditions.

Results

Mean scores and standard deviations for all conditions are shown as a function of level in **Table 2**. Analysis of variance revealed that the main effects of presentation level ($p<0.001$) and quiet-versus-noise ($p<0.01$) were significant, as was the level-by-quiet/noise interaction ($p<0.001$). (These and other analyses involving proportional data were accomplished with arcsine transformations to stabilize the error variance.) The main effect of initial versus final subtests was nonsignificant; but the presentation level by initial/final interaction was significant ($p<0.01$), reflecting the fact that the small differences between initial and final scores were in opposite directions for lower and higher presentation levels.

Table 2.
Percent correct means and standard deviations for all conditions in Experiment 1.

Level	(dB SPL)		20	28	36	44	52
Quiet	Initial	(Mean)	32.0	54.0	75.4	89.0	92.6
		(SD)	9.5	8.9	11.2	6.3	5.4
	Final	(Mean)	36.7	60.2	76.5	85.2	91.9
		(SD)	8.1	9.5	6.5	9.5	6.7
Noise	Initial	(Mean)	32.9	53.0	73.9	80.5	83.1
		(SD)	7.7	9.4	10.1	6.8	5.4
	Final	(Mean)	36.5	62.8	71.9	78.1	82.0
		(SD)	11.0	10.4	7.9	6.1	7.8

SD = Standard Deviation.

Figure 1 shows the performance-intensity (PI) function for overall scores as a function of level in dB SPL. Percent correct scores increased at a rate of about 2.5 percent per dB up to 36 dB SPL, and 0.8 percent per dB from 36 dB to 52 dB.

Figure 2 shows percent correct performance in quiet-versus-noise as a function of presentation level, collapsed across the initial and final subtests. The solid line refers to the quiet condition and the dashed line is for syllables presented in the presence of the babble at a +5 dB S/N ratio. Percent correct scores were the same in quiet and in noise at the two lowest levels, and diverge in the expected direction for the higher levels, reflecting the aforementioned level-by-condition interaction. Percent correct scores increased at 2.5 percent per dB in quiet and 2.4 percent per dB in noise up to 36 dB SPL, and slowed between 36 to 52 dB SPL to a rate of approximately 1 percent per dB in quiet and 0.6 percent per dB in noise.

Discussion

This experiment has generally revealed expected findings for the modified nonsense syllable test, in the sense that the results were similar to those obtained with the original NST. The unanticipated lack of a significant CV/VC difference is addressed in the General Discussion section. Some comment is appropriate here regarding the presentation level-by-quiet/noise interaction.

Because the S/N ratio was +5 dB for all noise conditions, the babble levels were only 15 and 23 dB SPL when

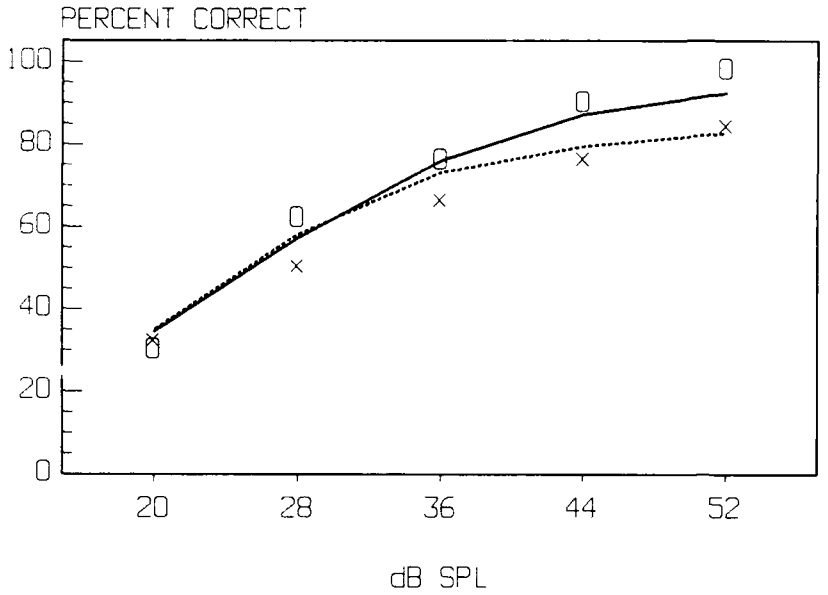

Figure 2.
Performance-intensity functions for the MNST in quiet (solid lines) and in noise (dashed lines). Corresponding data from Dubno and Levitt (5) for the original NST (quiet=O, noise=X).

the syllables were presented at 20 and 28 dB SPL, respectively. Thus, at these presentation levels the addition of the babble would yield little if any change compared to the ambient noise floor also present for the quiet condition, so that the task was effectively the same for both conditions. On the other hand, the relative contribution of the babble to the masking of the syllables would predominate over the noise floor with increasing presentation levels, so that a quiet-versus-noise effect would now become apparent. Because the S/N ratio is fixed, one might anticipate that the performance difference between the quiet and noise conditions would become essentially constant for levels above 52 dB SPL. However, this point cannot be accepted on face value because, for example, Stelmachowicz *et al.* (11), found that speech recognition scores of normal listeners differed at 60 and 80 dB SPL for monosyllabic words presented in noise.

The current findings are compared to analogous data using the original NST reported by Dubno and Levitt (5) in **Figure 2**. The original NST data are shown by circles for scores in quiet and Xs for scores in noise. Recall that the current data are based upon only the /a/-subsets, whereas the 1981 means are based upon three vowel subsets, (i.e., /i/, /a/, and /u/). The agreement between the two sets of data is impressive. The slopes of the functions for the quiet and noise conditions for the original and modified NSTs are similarly close: in quiet, the overall slope is 1.81 percent per dB for the modified NST compared to 1.93 percent per dB for the original test. In quiet, performance on the modified NST rises at an overall rate of 1.50 percent per dB, which also compares favorably with 1.57 percent per dB as reported by Dubno and Levitt (5).

These findings indicate that the stimulus modifications involved in removing the carrier phrases, and the effects of increasing the response alternatives to include all consonants represented in the test, did not appreciably affect performance on the NST.

EXPERIMENT II

The second part of the study addressed the nature of the errors made on the modified nonsense syllable test (MNST). This was done to determine what errors and confusions are to be expected on the MNST when normal listeners hear the materials at clearly audible levels. It also reveals the responses that are obtained in the absence of any experimental manipulations that might be introduced by an investigator using the test. Analyzing the responses is necessary because some differences in confusions among consonants might be expected on the modified test compared to the original NST. These differences might occur for at least two reasons. First, the number of response alternatives was expanded from the seven to nine most likely ones in the original NST to essentially all possible alternatives (22 for CVs and 16 for VCs) in the modified version. Hence, a perceived error consonant that is not among the possible choices in the original NST would necessitate a different choice as the response, whereas the consonant actually heard would more likely be a viable response on the MNST. The most obvious example would be the ability of the MNST to reveal voicing confusions

not possible on the original NST. Moreover, Bell, Dirks, and Kincaid (12) recently demonstrated that confusion patterns depended upon the number of response alternatives.

The second likely reason to anticipate different errors between the NST and the MNST is that the test tokens are surrounded by a carrier phrase in the NST but are presented in isolation in the modified version. Hearing only the isolated test syllable denies to the listener an immediate frame of reference regarding the speech acoustics and timing of the talker that might be derived from being in the context of the carrier (especially for CVs). It is also possible that the editing process may have removed parts of the signal, including coarticulatory information, thereby affecting specific confusions, although this is unlikely.[2]

Subjects

There were 15 subjects in this experiment, including 14 females and one male. These subjects ranged in age from 18 to 21 (mean 24) years and met the same criteria for normality used in Experiment I.

Procedures

The materials were presented monaurally at 44 and 52 dB SPL, which were the two highest levels used in Experiment I, and where high percent correct scores were found. Testing was done at both 44 and 52 dB SPL as a compromise to achieve the somewhat conflicting goals of generating a reasonably sufficient number of errors to analyze while at the same time keeping the presentation levels high enough to reflect typical performance for when the test materials are audible and undistorted. The MNST was administered both in quiet and in the context of equalized cafeteria babble (at an S/N ratio of +5 dB) to provide typical normal results under both conditions, which are frequently used in speech recognition applications. Because 44 and 52 dB were also the levels where a performance difference was found between the quiet and noise conditions in Experiment I, testing at these levels was expected to reveal differences in errors between the quiet and noise conditions.

[2]The "cuts" made in the waveform editing process were almost always during silences indicated by no energy on the computer screen and verified by listening to the samples. The syllable segments within, and extracted from, the carriers were indistinguishable both visually and by listening. The only exception was the case of the CV syllable /sa/. Here, a /k/-like coloring (carried over from the word "mark" in the carrier phrase) at the onset of the /s/ could not be removed unless cuts would have been made well into the sibilant noise, and was thus retained in the digitized file for the /sa/ syllable. However, this isolated problem was of no consequence because (a) it was heard only while editing the digitized master, and was not audible on any of the test tapes; and (b) there was not even a single confusion between /s/ and /k/ for any of the subjects under any of the conditions.

Table 3.
Percent correct means and standard deviations in Experiment II.

		Quiet	Noise
Initial	(Mean)	95.1	87.9
	(SD)	2.9	3.2
Final	(Mean)	92.7	84.8
	(SD)	5.0	5.9

SD = Standard Deviation.

Ten replications were administered for each condition, which is typical of experiments addressing confusion data. Thus, each subject listened to a total of 80 test lists [2 levels (44/52 dB) × 2 conditions (quiet/noise) × 2 consonant positions (CV/VC) × 10 replications]. The test lists were administered in random order over the course of several listening sessions, which varied in number according to the availability of the subjects.

All testing was done individually under the same conditions as described for Experiment I, and included familiarization and practice before data collection.

Results

Percent correct consonant recognition performance is summarized in **Table 3**. Analysis of variance revealed that performance was significantly better in quiet than in noise ($p<0.001$) and for CVs than for VCs ($p<0.01$). Their interaction was nonsignificant.

Stimulus-response (confusion) matrices from the data pooled across subjects were constructed for the four conditions (CVs and VCs in quiet and in noise). Such matrices depict the relationship between stimuli (or target) consonants in rows and the phonemes given as responses in columns. Thus, for the MNST these matrices involve 22×22 cells for CVs and 16×16 cells for VCs. Correct identification is revealed by cells along the diagonal, and the values in these cells are easily converted into percent correct identification scores for each consonant presented.

As expected, percent correct identification scores varied among the consonants. These data are summarized as a function manner and place of articulation (13) in **Figure 3** and **Figure 4**, respectively. The figures reveal that correct consonant recognition was nearly perfect for the semivowels, affricates and nasals; worst for the fricatives; and second poorest for the stops; it principally involved consonants with front places of articulation ($p<0.01$).

Most of the errors on the MNST were due to the mis-

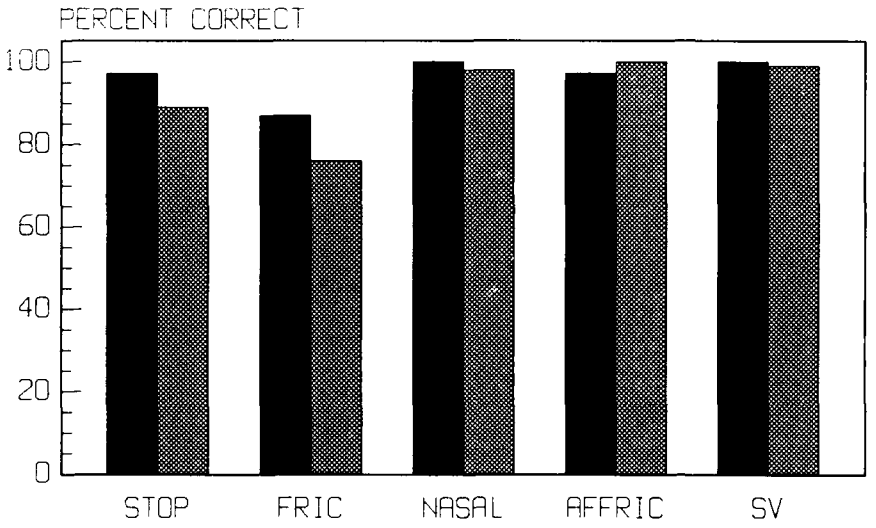

Figure 3.
Correct consonant identification in terms of manner of articulation. Solid bars show data obtained in quiet, and crosshatched bars show data in noise.

identification of a fairly small number of individual consonants. **Table 4** presents the correct identification percentages for the consonants that had scores of ≤ 90 percent for one or more of the four conditions, which include the most poorly recognized phonemes on the MNST. As expected from **Figure 3** and **Figure 4**, all of these consonants were fricatives or stops, and all but one (/h/) had anterior places of articulation. (Performances for /k/ fell only slightly below 90%, and this occurred for only one condition.)

The confusions that exceeded a chance rate of occurrence were determined from the confusion matrices, and are tabulated in **Table 5**. For each confusion in this table, the first phoneme is the stimulus (or target) consonant, and the second is the response given for

Table 4.
Poorly identified consonants on the MNST and their percent correct identification scores.

	Quiet		Noise		
Consonant	**Initial**	**Final**	**Initial**	**Final**	**Overall**
p	98.3	98.0	75.7	87.3	89.8
k	100.0	99.3	86.3	96.3	95.5
b	80.7	98.0	57.3	91.3	81.8
f	95.3	82.7	75.0	41.3	73.6
θ	89.3	52.3	76.0	47.3	66.3
v	55.0	87.0	41.0	62.7	61.4
ð	91.7	70.3	82.7	55.3	75.0
h	92.7		60.7		76.7

Table 5.
Confusions exceeding chance expressed as a percentage of the responses to the target (stimulus) consonant.

Confusions*	**Initial Quiet**	**Initial Noise**	**Final Quiet**	**Final Noise**
v b	25.3	29.7	11.3	31.7
b v	11.7	26.3		
θ f		11.3	42.0	24.3
f θ				11.0
ð d		8.0	11.7	28.7
v ð	15.3	20.7		
ð v			8.0	
f p			9.3	37.7
p f				7.7
h p	6.3	32.7		
p h		16.3		
b ð	6.0	11.7		
k h		7.0		
h k		4.7		
f v		9.7		
f b		8.7		
θ t				7.7
θ s		6.3		
p k	5.0			
g d		6.7		
tʃ j	6.0			

*First consonant is the target, second is the response.

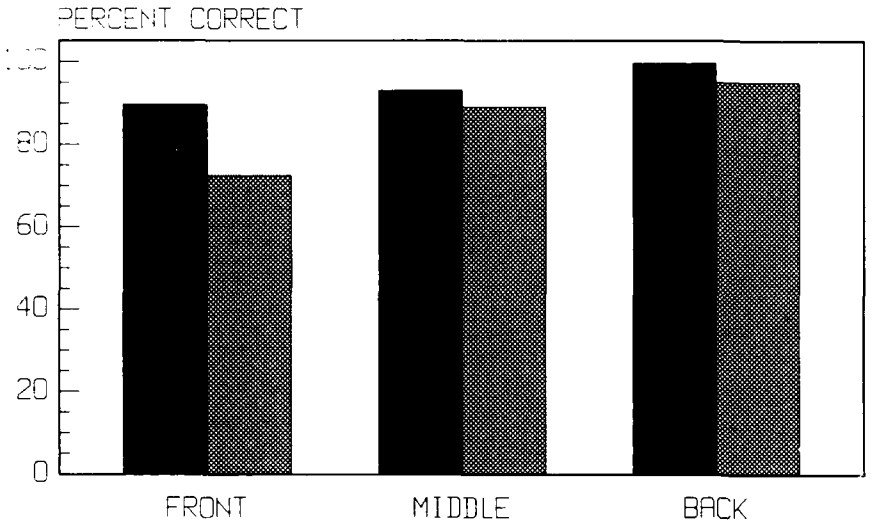

Figure 4.
Correct consonant identification in terms of place of articulation. Solid bars show data obtained in quiet, and crosshatched bars show data in noise.

Table 6.
Percentages of confusions exceeding chance involving errors of place of articulation, manner and/or voicing.

Condition		Place (P)	Manner (M)	Voicing (V)	P+M	P+M+V
Initial	Quiet	22	8		70	
	Noise	24		5	67	4
Final	Quiet	61			39	
	Noise	24			76	

that stimulus (e.g., "v b" followed by "25.3" indicates that /v/ was heard as /b/ 25.3 percent of the time). The confused pairs in this table are arranged roughly in descending order of occurrence, keeping both directions of confusions between two phonemes (e.g., /v,b/ and /b,v/) together. This table indicates that confusions were principally among consonants sharing anterior places of articulation. Furthermore, the response consonants tabulated in the table are largely consistent with the response biases of normal subjects reported for the original NST (5).

Table 6 shows the percentages of errors of specific place of articulation (e.g., bilabial, alveolar), manner, and/or voicing among confusions exceeding chance. Place-only errors predominated for VCs in quiet, but most of the confusions in the three other conditions were combined place/manner errors. Nine percent of the confusions exceeding chance for CVs in noise involved voicing errors.

Discussion

Most of the consonant identification errors involved anterior sounds, and confusions exceeding chance were principally among consonants sharing anterior places of articulation. These findings likely reflect acoustical similarities among the confused sounds (5). Most of these confusions have also been found for the corresponding subtests of the original NST (14).

Unlike the preponderance of combined place/manner errors found here for the MNST, a plurality of place errors has been reported for the original NST (5). It is unlikely that the high proportion of place/manner errors here reflects increased random guessing compared to the original test. This is so because these confusions were found among confusions exceeding chance in the current study, implying that they reflect a systematic effect.[3]

GENERAL DISCUSSION

Overall, the modified nonsense syllable test yields results comparable to those of the original NST. Several points, however, do deserve some comment.

The reason for the absence of the expected significant difference between CV and VC scores in Experiment I is unclear, particularly because the typical finding of higher CV than VC scores was observed in Experiment II. One possibility, which may explain why the VC scores were higher at 20 and 28 dB, may relate to the relative levels of the consonant and vowel portions of the syllable in the absence of a preceding carrier signal. At these low levels, the presence of the relatively more audible vowel energy may have served as a signal to attend to the consonant

[3]Actually, the proportions of place, place/manner, etc., errors found here were virtually the same regardless of whether we used all confusions or just those exceeding chance.

information in VC condition. For the CV condition, however, the attention-getting attribute of the relatively more audible vowel energy would occur too late to be used. The small difference between the CV and VC scores indicated that this effect, if actually present, is rather small. At 44 and 52 dB SPL, where the syllables were quite audible and their onsets were apparent, the small differences between initial and final scores were in the expected direction.

A possible explanation for the large representation of place/manner errors involves two facets: the first point addresses the contrast in the data obtained in quiet. Here, most of the CV confusions (70 percent) were place/manner errors, whereas the majority of VC confusions (61 percent) were place-only errors. Also, note that all place/manner confusions exceeding chance involved stop/frication errors (**Table 5**). Because the CVs were preceded by silence instead of a carrier phrase which might serve as a marker, it is possible that the perceived duration of initial position consonant noise became ambiguous, thereby increasing the number of stop/fricative confusions. The audible representations of cues for the stop/fricative distinction in the VCs would not be subject to such ambiguity, and so VC errors in quiet would be less likely to involve a manner of articulation confusion. Second, larger proportions of place/manner errors occurred for both initial and final consonants in noise. This suggests that the babble obscured manner cues, which should affect both CVs and VCs because the babble is continuously present. This point is consistent with the original NST data, where the representation of place/manner errors was much greater in noise than in the quiet condition.

In summary, a modified nonsense syllable test has been developed by replacing the multiple subtests of the original NST with a 22-item CV subtest and a 16-item VC subtest. All test items are presented as isolated syllables (i.e., without a carrier phrase). The response alternatives for each stimulus syllable encompass virtually all possible consonants in the initial and final positions, respectively. These changes make it possible to resolve confusions not possible on the original NST, and also make it possible to generate a single confusion matrix for each subtest, should one desire this capability. The modified test results in findings that compare favorably to those previously reported for the original NST. In other words, the benefits for various applications afforded by these changes do not come at the cost of compromising the already proven integrity of the NST. Therefore, one may conclude that the modified NST described here constitutes a useful tool for assessing speech recognition at the syllable level.

ACKNOWLEDGMENTS

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ABSTRACTS OF RECENT LITERATURE

by
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Abstracts are drawn primarily from the orthotics and prosthetics literature. Selections of articles were made from these journals:

American Journal of Physical Medicine and Rehabilitation
American Journal of Sports Medicine
Assistive Technology
Canadian Journal of Occupational Therapy
Ergonomics
International Journal of Rehabilitation Research
Journal of Biomechanics
Journal of Bone and Joint Surgery
Paraplegia
Physical Therapy
Scandinavian Journal of Rehabilitation Medicine

PROSTHETICS, ORTHOTICS, AND RELATED TOPICS

Benefits of Sport and Physical Activity for the Disabled: Implications for the Individual and for Society. Shephard RJ, reprinted from *Scand J Rehabil Med* 23:233-241, 1991.

An increase of physical activity is commonly recommended to those with physical disability, but it is necessary to distinguish competitive sport from fitness programmes, remedial gymnastics and active recreation. Potential benefits of enhanced activity are reviewed. Likely psychological gains include an improvement of mood-state, with a reduction of anxiety and depression, an increase of self-esteem and feelings of greater self-efficacy. Sociological gains include new experiences, new friendships, and a countering of stigmatization. Perceived health is improved, and in a more long-term perspective there is a reduced risk of many chronic diseases. Finally, there is a greater likelihood of employment, with less absenteeism and enhanced productivity. Both the health and the industrial benefits have a potential to yield cost savings that could make an important contribution toward the expense of suitably adapted physical activity programmes. It is concluded that the physically disabled should be encouraged to engage in physical activity, although further large-scale longitudinal studies are needed to determine the optimal type of programme for such individuals.

Biomechanical Analysis of the Influence of Prosthetic Feet on Below-Knee Amputee Walking. Gitter A, Czerniecki JM, DeGroot DM, reprinted from *Am J Phys Med Rehabil* 70:142-148, 1991.

Although energy storing prosthetic feet have achieved widespread clinical acceptance, the effect of these components on the biomechanics of below-knee amputee gait is poorly understood. The purpose of this study was to determine the biomechanical adaptations used by the below-knee amputee while wearing a conventional prosthetic foot and to assess the influence of energy storing prosthetic feet on these adaptations. Mechanical power outputs of the lower extremity in five normal and five below-knee amputee subjects using the SACH, Seattle and Flex feet were studied. Ground reaction forces and kinematic data were collected at a walking speed of 1.5 m/s and were used to determine the muscular power outputs of the lower extremity during stance. Consistent patterns of muscular power output at the hip and knee of the residual limb occur. While wearing the SACH foot, negligible energy generation occurs at the prosthetic foot during pushoff. A decrease in energy absorption at the knee during the first half of stance and an increase in energy generation by the hip extensors were the major adaptations noted in the proximal muscle groups. Compared to the SACH foot, the energy storing feet demonstrated increased energy generation during pushoff. Despite the improvements in the performance of the energy storing prosthetic feet, no significant differences were found in the pattern or magnitude of knee and hip power outputs compared to the SACH foot.

Biomechanical Model of the Human Shoulder Joint—II. The Shoulder Rhythm. Hogfors C, Peterson B, Sigholm G, Herberts P, reprinted from *J Biomech* 24:699-709, 1991.

A method to investigate the rhythm of the human shoulder, i.e. the interplay between the motion of constituent parts of the shoulder, has been devised and tested. The method is based upon numerical evaluation of low dose roentgenstereophotogrammetric motion pictures of subjects equipped with radiation dense implantations in the bones. Evaluation of the method shows that it may be used in determining motion patterns and that the employed interpolation techniques can be used to simulate motions not actually performed in the laboratory. The shoulder rhythm has been previously poorly investigated and quantified results published pertain to one plane only. Our results on motion patterns correlate with previous investigations. With this method, we show that the absolute position of the bones varies significantly between individuals while the relative displacement of the bones during motion exhibit similarities. In particular the results show that, under normal conditions, the individual rhythm is very stable and insensitive to small hand-loads.

Conductive Differences in Electrodes Used with Transcutaneous Electrical Nerve Stimulation Devices. Nolan MF, reprinted from *Phys Ther* 71:746-751, 1991.

The purpose of this study was to document conductive differences among commercially available electrodes used with transcutaneous electrical nerve stimulation (TENS) devices. Impedance within a model system involving a human subject was calculated from oscilloscopic tracings of the pulse waveform for each of 25 different electrode types. Impedance values ranged from 1,000 to 7,800Ω. Possible reasons for these differences are discussed. The observation that electrodes vary in their impedance and can thereby affect the stimulus applied to the skin raises the question of whether electrode choice might affect the clinical effectiveness of TENS. Attention is drawn to the skin electrodes as a variable that may affect the results of clinical and basic studies involving TENS.

Development of an Integrated Wheelchair Tray System for Augmentative Communication. Blackstein-Adler S, Ryan S, Naumann S, Parnes P, reprinted from *Assist Technol* 2:142-150, 1991.

This paper describes the development of a wheelchair tray system for persons with physical disabilities who require an augmentative communication system. The tray system offers advantages over existing systems by providing a convenient anterior/posterior tilt feature, a means for stowing the tray when not in use, and a method of accommodating communication systems and powered wheelchair controls. Caregivers of seven subjects fitted with the prototype system assessed its performance through the completion of questionnaires provided at the end of 6-week field trials. The technical performance of the system was also monitored. The prototype system was favorably received by six participants. Several recommendations are made to further increase consumer acceptance of the final tray design.

The Effect of Ankle Constraint on the Torsional Laxity of the Knee During Internal-External Rotation of the Foot. Quinn TP, Mote CD, Skinner HB, reprinted from *J Biomech* 24:511- 525, 1991.

The *in vivo* torsional laxity and stiffness of the knee joint are usually determined by rotating the foot and measuring the torque generated at the knee. However, when rotation is applied to the foot, significant three-dimensional forces and moments are produced at the knee. These forces and moments depend upon the external constraint of the ankle complex, and as a result, the observed laxity of the knee also depends on the ankle constraint. Tests are conducted with the foot of a subject in a shoe, with and without the ankle taped, and in a buckled and unbuckled (ski) boot that can effectively constrain ankle rotation. The average laxity of the primary (linear) region of the axial moment vs internal-external rotation is 30% greater when the ankle is constrained by the buckled boot than it is in three other cases of lesser ankle constraint.

Effectiveness: A Neglected Dimension in the Assessment of Rehabilitation Devices and Equipment. Conine TA, Hershler C, reprinted from *Int J Rehabil Res* 14:117-122, 1991.

Effectiveness is a term used by research methodologists when referring to the attributes of a new health care intervention (e.g. device, medication, or procedure) which if lacking may result in its rejection despite its efficacy and efficiency. Administrators and consumers increasingly require evidence to ensure that a proposed new product or manoeuvre not only 'works' (efficacy, efficiency) but is 'practical' (effective). Yet, effectiveness data are rarely described in research literature or adequately measured. Common effectiveness qualities that might be considered in the formal evaluation of new rehabilitation devices and equipment are cost, convenience to the user ('user-

friendliness'), and compliance with the local standards. This article identifies some of the most important variables related to these attributes and suggests strategies for appropriate data collection and analysis. A comparison of two products evaluated in an institutional setting is used to illustrate the suggested method.

Effectiveness of Orthotic Shoe Inserts in the Long-Distance Runner. Gross ML, Davlin LB, Evanski PM, reprinted from *Am J Sports Med* 19:409-412, 1991.

Five hundred questionnaires were distributed to long-distance runners who had used, or who were using orthotic shoe inserts for symptomatic relief of lower extremity complaints. Three hundred forty-seven (69.4%) responded (males, 71%; females, 29%). The mean age of the respondents was 36 years (range, 15 to 61). The average distance run per week was 39.6 miles (range, 5 to 98). The mean duration for use of the orthotic inserts was 23 months (range, 1 to 96). The predominant (63%) type of orthotic device used was flexible. The presumed diagnoses in the population studied were excessive pronation (31.1%), leg length discrepancy (13.5%), patellofemoral disorders (12.6%), plantar fasciitis (20.7%), Achilles tendinitis (18.5%), shin splints (7.2%), and miscellaneous (4.9%).

Of the runners responding, 262 (75.5%) reported complete resolution or great improvement of their symptoms. Results of treatment with orthotic shoe inserts were independent of the diagnosis or the runner's level of participation. A high degree of overall satisfaction was demonstrated by the finding that 90% of the runners continued to use the orthotic devices even after resolution of their symptoms. Orthotic shoe inserts were most effective in the treatment of symptoms arising from biomechanical abnormalities, such as excessive pronation or leg length discrepancy. Along with other conservative measures, orthotic shoe inserts may allow the athlete to continue participation in running and avoid other treatment modalities that are more costly and time consuming, and therefore less acceptable to them.

The Effects of Splinting on the Spastic/Hemiplegic Hand: Report of a Feasibility Study. Langlois S, Pederson L, MacKinnon JR, reprinted from *Can J Occup Ther* 58:17-25, 1991.

Hand splints are used by occupational therapists as a method of reducing the increased muscle tone of the upper extremity following stroke. However, the paucity of research and inconsistent findings examining the effects of splinting on spasticity has resulted in this technique being a controversial one. Many parameters of splinting need to be investigated, such as the type of splint, the duration of use, and wearing schedules. This feasibility study was conducted to pretest instruments and procedures investigating the effects of a finger spreader on the spastic musculature of the wrist and to examine trends in spasticity associated with variables, including a splint wearing schedule, expectations and satisfaction with the splint, and compliance.

Nine subjects were randomly assigned to three groups defined by wearing schedules of twenty-two, twelve, and six hours per day. The greatest change in the level of spasticity was noted in the group wearing the splint for twenty-two hours. However, this trend was not statistically significant. A statistically significant relationship was found between expectations of the splint and compliance to the wearing schedule. Satisfaction with the splint outcome and therapeutic interaction was also observed to have a statistically significant relationship with compliance. This indicates that the procedures and measures designed for this study are worth pursuing in future research.

Hand Strength: The Influence of Grip Span and Grip Type. Fransson C, Winkel J, reprinted from *Ergonomics* 34:881- 892, 1991.

The maximal force from each of the fingers II-V (FF) and the resultant force between the jaws of the tool (RF), due to contribution from all fingers, were measured using a pair of modified pliers. The RF was measured at 21 handle separations and the FF was measured at seven handle separations for each finger. A traditional grip type was compared with a 'reversed' grip where the little finger was closest to the head of the tool. Sixteen subjects (8 females and 8 males) participated in the study.

Both the RF and FF varied according to the distance between the handles. For both grip types, the highest RF was obtained at a handle separation of 50-60 mm for females and 55-65 mm for males. For wide handle separations, the RF was reduced by 10% (cm increase in handle separation)$^{-1}$. The force-producing ability of the hand was influenced by the grip type and the highest RF was obtained when using the traditional grip. An interaction was found between the fingers, i.e., the maximal force of one finger depended not only on its own grip span, but also on the grip spans of the other fingers. About 35% of the sex difference in hand strength was due to hand size differences.

International Wheelchair Standards: A Study of Costs and Benefits. Hartridge M, Seeger BR, reprinted from *Assist Technol* 2:117-123, 1991.

We hypothesized that extra costs incurred in meeting the requirements of wheelchair standards are recouped within the life of the wheelchair. We selected standards-quality and non-standards-quality electric wheelchairs of the same make and subjected them to accelerated life tests in a laboratory to simulate 1 year's active use. Expenses and lost time incurred due to breakdowns were monitored, and the costs of upgrading were documented. Our results support the hypothesis, within the limits imposed by the availability of only a small number of makes of electric wheelchairs of recognized standards quality. The significance of this finding is that wheelchair standards can be used to upgrade wheelchair quality in a cost-effective manner.

Invariant Characteristics of Gait Initiation. Brunt D, Lafferty MJ, McKeon A, *et al.*, reprinted from *Am J Phys Med Rehabil* 70:206-212, 1991.

Studies were undertaken first to describe the invariant characteristics of gait initiation and second to better understand the function of each limb in the process of gait initiation. Analysis of variance indicated significant main effects for speed for time to onset of EMG activity and force plate recordings, time to swing toe-off and heel-strike and stance toe-off. However, when the dependent variables were expressed as a percentage of the initiation cycle, no significant main effects were noted. For the second study, two force plates were utilized, and reflective markers were placed on the sacrum and anterior superior iliac spines. The timing of heel-strike of the swing limb and toe-off of the stance limb showed a high degree of coordination in both experiments (r=0.95 and 0.98). It was concluded that the relative invariance of selected parameters indicates that gait initiation is centrally programmed. It also appears that the swing limb, although forces were very small, is responsible for the initial weight shift to the stance limb and that the stance limb is then primarily responsible for the generation of momentum.

Occupational Performance of Activities of Daily Living among Elderly Canadians in the Community. McKinnon AL, reprinted from *Can J Occup Ther* 58:60-66, 1991.

Sociocultural role expectations for occupational performance by individuals and groups differentiated on the basis of age, gender, and other social characteristics are of central interest to occupational therapy practice based on the occupational performance model. Data analysed from the public use microdata file of the 1985 General Social Survey of Canadians reveal important differences in social role expectations and patterns of occupational performance among a representative sample of elderly Canadians (N=3.130), as evidenced by their social support for certain activities of daily living. Significant gender and age differences are identified in the types and sources of social support provided and received, with elderly men much more likely than elderly women to receive help with housework, meal preparation, and grocery shopping. Such information contributes to the development of a broad national context for the client-centred practice of occupational therapy with elderly Canadians, and points to the need for further research on sociocultural influences on occupational performance across the lifespan.

Physiological Responses to Maximal Exercise on Arm Cranking and Wheelchair Ergometer with Paraplegics. Martel G, Noreau L, Jobin J, reprinted from *Paraplegia* 29:447-456, 1991.

The study describes the responses of 20 paraplegic athletes (mean age: 26.8 ± 1.6 years) to a continuous incremental workload test until exhaustion on an arm cranking ergometer (ACE) and on a wheelchair ergometer (WCE). Both ergometers used the same electromagnetic braking device allowing a fair comparison between results. Tests were conducted at a 24 hour interval at the same time of the day. Oxygen uptake (VO_2), heart rate (HR), workload (W), blood pressure (BP), Borg index, and mechanical efficiency (ME) were measured at every minute during the effort and the cool down periods of both tests. The purpose of this study was to analyse the different responses obtained on ACE and on WCE during maximal effort by paraplegics, and also to determine which ergometer permits the higher ME. Results indicate that paraplegics reached the same max HR on ACE and on WCE (97% of the predicted max HR). The lack of significant difference ($p < 0.05$) between ACE and WCE in terms of maximal values of VO_2, VE and HR suggests that the subjects reached their maximal capacity on each test regardless of the type of ergometer. Nevertheless, W max (in Watts) was 26% higher on ACE than on WCE. Maximal ME values were respectively 16% and 11.6% on ACE and WCE. Results suggest that ergometers and protocol used in this study are appropriate to measure physiological responses of paraplegic athletes during arm cranking and wheelchair exercise without excessive or early arm fatigue.

Postural Load and Back Pain of Workers in the Manufacturing of Prefabricated Concrete Elements. Burdorf A, Govaert G, Elders L, reprinted from *Ergonomics* 34:909-918, 1991.

In a population of male workers in a concrete manufacturing plant (n=114), the occurrence of back pain was studied in relation to a control group of maintenance engineers (n=52). The prevalence of back pain in the 12 months preceding the investigation was 59% among the concrete workers, and 31% among the controls. After excluding persons with existing back pain before starting work in the present factory, a comparison between concrete workers and maintenance engineers showed an age-adjusted odds ratio for back pain of 2.80 (1.31-6.01). Postural load of workers in both plants were measured using the Ovako Working Posture Analysis System. During 4009 observations working postures concerning the back, lower limbs, and lifting activities were recorded. The average time spent working with a bent and/or twisted position of the back was found to contribute to the prevalence of back pain. The results of this study also suggest that exposure to whole-body vibration, due to operating vibrotables, is a second risk factor for back pain.

Prediction of Amputation After Severe Lower Limb Trauma. Robertson PA, reprinted from *J Bone Joint Surg* 73-B:816-818, 1991.

The Mangled Extremity Severity Score was applied to 152 patients with severely injured lower limbs. All cases with a score of seven or more required amputation; some with scores of less than seven eventually came to amputation. These observations are discussed.

Prosthetic Replacement of the Distal Femur for Primary Bone Tumours. Roberts P, Chan D, Grimer RJ, *et al.*, reprinted from *J Bone Joint Surg* 73-B:762-769, 1991.

Over a 16-year period, 135 custom-made distal femoral prostheses, based on a fully constrained Stanmore-type knee replacement, were used in the treatment of primary malignant or aggressive benign tumours.

Survivorship analysis showed a cumulative success rate of 72% at five years and 64% at seven years. Intact prostheses in 91% of the surviving patients gave good or excellent functional are results. Deep infection was the major complication, occurring in 6.8% of cases; clinical aseptic loosening occurred in 6.0%. Revision surgery was carried out for loosening and infection, and the early results are encouraging.

We conclude that prosthetic replacement of the distal femur can meet the objectives of limb salvage surgery.

Social Role Functioning Following Spinal Cord Injury. Stambrook M, MacBeath S, Moore AD, *et al.*, reprinted from *Paraplegia* 29:318-343, 1991.

The Katz Adjustment Scale—Relatives Form was completed by the wives of 27 hospital-discharged spinal cord injured (SCI) patients. Their ratings of the spouses' social adjustment and behaviour were compared to available community and psychiatric norms. Overall, spouses rated their SCI husbands as performing significantly more socially inappropriate behaviours compared to ratings of 'normals' but as engaging in significantly less socially inappropriate behaviours compared to the ratings of psychiatric patients. SCI patients were perceived as performing the same levels of social activities as 'normals,' but engaging in less free-time activities compared to both 'normals' and psychiatric patients. These results mirror similar analyses comparing moderate and severe head injury victims with normal and psychiatric norms. The implications for rehabilitation and counselling of families of traumatically disabled patients are discussed.

Special Facilities and Services for University Students with Mobility Impairment: A Demographic Study (U.S.A.). Huer MB, reprinted from *Assist Technol* 2:125-130, 1991.

The purpose of this study was to collect demographic information in 1988-1989 regarding the use of technology in disabled student services programs in higher education. Two different methods were selected: (a) the frequency of availability of 21 special services was tallied in 593 university programs across the United States, and (b) a self-administered mail questionnaire was used to gather information from 150 randomly selected programs. The rate of response to the survey was 65%; 98 questionnaires were returned from programs in 38 states. The results of the studies summarize the special services and facilities generally accessible to disabled university students, the technological assistance available, the numbers of university students having disabilities of mobility, the numbers who need assistance for computer access, and the percentage of programs identifying disabled students using electronic devices. These demographic data may shed new light on current practices related to rehabilitation technology in university settings.

Spinal Injury Rehabilitation: Do Staff and Patients Agree on What They are Talking About? Glass CA, Krishnan KR, Bingley JD, reprinted from *Paraplegia* 29:343-349, 1991.

The psychological effects of spinal cord injury on patients themselves have been discussed in a number of articles, but few studies have been made of patients and staff, perceptions of the effectiveness of the treatment they receive and supply.

An earlier investigation by the present authors showed that there were differences between the views of staff and of patients in terms of their understanding of rehabilitation. As a consequence, a number of procedural changes were implemented in the Spinal Unit, in an attempt to improve the information provided for patients and their relatives, and the selection and support of staff.

Reanalysis of the staff and patient views of rehabilitation were carried out 12 months later using a standardised questionnaire and any changes in response were noted.

The present findings are analysed, and the potential implications for other units are noted.

Talocrural and Talocalcaneal Joint Kinematics and Kinetics During the Stance Phase of Walking. Scott SH, Winter DA, reprinted from *J Biomech* 24:743-752, 1991.

The purpose of this investigation was to study the kinematics and kinetics of the joints between the leg and calcaneus during the stance phase of walking. The talocrural and talocalcaneal joints were each assumed to act as monocentric single degree of freedom hinge joints. Motion at one joint was defined by the relative rotation of a point on the opposing joint. The results, based upon the gait of three subjects, showed that the hinge joint assumption may be reasonable. A discrepancy in the kinematics was shown between the talocrural joint rotation and its commonly assumed sagittal plane representation, especially during initial flatfoot. This discrepancy is due to the fact that the sagittal plane rotation is created by the combined rotations of the talocrural and talocalcaneal joints. The talocalcaneal joint showed a peak 25-30 Nm supinatory moment at 80% of stance. The talocrural joint moment was qualitatively similar to the commonly measured sagittal plane moment, but the present results show that the sagittal plane moment overpredicted the true moment by 6-22% due to the two-dimensional assumption.

Upward Displacement of the Centre of Gravity in Paraplegic Patients. Duval-Beaupere G, Robain G, reprinted from *Paraplegia* 29:309-317, 1991.

The centres of gravity of 44 complete chronic spinal cord injured patients and 24 normal subjects were measured using a gamma ray scanner (Barycentremetre). The results are expressed as a percentage of body length and as anatomical level. The mean weight of paraplegic patients was 12 kg less than the controls. The centre of gravity was 5% of body length higher in the paraplegic patients than in the controls, equivalent to 3 to 4 vertebrae level. The importance of such changes in the centre of gravity for the design of stable wheelchairs is discussed.

BOOK REVIEWS

by
Jerome D. Schein, Ph.D.; Franklyn K. Coombs; William De l'Aune, Ph.D.; Bruce Blasch, Ph.D.; Alexandra Enders, O.T.R.

Speech Synthesis. Technology for Disabled People. Alistair D.N. Edwards. Baltimore: Paul H. Brookes, 1991, 157 pp. Illustrated.
by Jerome D. Schein, Ph.D., Professor Emeritus of Sensory Rehabilitation, New York University, and David Peikoff Chair in Deafness Studies, University of Alberta, Edmonton, Canada

The young engineer who wrote this book addresses two rehabilitation problems: a) providing a voice for those who have lost theirs; and, b) replacing visual displays with vocal outputs for those who cannot see. In surveying both paradigms, Edwards delves into both the pluses and minuses of technical solutions, and he peers into the future to assay directions these technologies may take.

Before tackling the specifics, Edwards provides two chapters on technical problems facing developers and users of synthesized speech. Despite the esoteric nature of some of the issues—phonetics, prosody, paralinguistics, computer-interface requirements, etc.—these chapters are easy to read, because the author has mastered the art of stating complex material (with which some of the readers may not be familiar) in simple terms they do know or can quickly master from brief definitions. Consider the following:

> One approach to dealing with the problem of differing pronunciation of phonemes is to recognize that variations on the basic phonemes exist, which are known as *allophones*. They are not separate phonemes, because if one was substituted for the other in a word, that word would still be recognizable—it just might sound a little odd. As with phonemes, linguists disagree as to how many distinct allophones there are in the English language, but high-quality speech synthesizers have been developed on the basis of around sixty of them (p. 17).

That example typifies the text, making it accessible to readers who are not familiar with some of the technology involved in synthesizing speech.

Following his general discussions, Edwards focuses on some specific products. He describes and evaluates Equalizer, Light Talker, Touch Talker, Dolphin Hal, Frank Audiodata, and the Kurzweil Personal Reader. These all manage text: either text-to-speech or speech-to-text. In another chapter he describes techniques for dealing with graphics using programs like Outspoken and Soundtrack. These latter are critical for blind computer users. Edwards urges, on their behalf, that "adapted auditory interfaces must exploit sounds in a more imaginative manner" than they now do.

Peering into the future, Edwards looks to articulatory synthesis as a way of attaining better quality speech synthesis. He foresees a music manuscript processor that will supplant braille for blind composers. Finding faster means of inputting speech is another area that Edwards believes will bear fruit in the near future. He raises questions about reading machines in the 'paperless offices' of the future. Tailoring speech outputs to particular individuals so that their use of synthesized speech would not be noticeable appears to Edwards as a dream. Another dream: all computer interfaces will be based on multiple media, "just as human communication is." Edwards cautions, however, that "It is the decisions which designers make when they are not thinking about the needs of disabled users which usually have the greatest effect on them" (p. 122).

Edwards is a considerate author with a generous publisher. While he writes from a British perspective, he consistently points to U.S. counterparts or, lacking those, provides adequate references to enable readers to find what they want in either country. The text is also well-indexed and contains several helpful appendices.

Do-It-Yourself Listening and Signaling Devices for People with Hearing Impairment. Revised Edition. William Paschell. Wheaton, MD: Author (3717 May Street), 1991, 58 pp. Illustrated.
by Jerome D. Schein, Ph.D.

The author holds the Chair of Assistive Devices, Washington Area Group for the Hard of Hearing, and

Veterans Organization for the Hearing Impaired. His organizational experiences and his own hearing impairment have sensitized him to the range of this disability, from mild to deaf. Accordingly, his self-help manual concerns itself with a broad array of devices, not just those for persons with mild to moderate losses but also those for persons with severe to profound losses. In addition, Mr. Paschell lists equipment sources and accessible ELDERHOSTELS, advises on how to set up an assistive-device center, and essays about practical means of managing the daily problems facing persons with impaired hearing.

The text is clearly written, avoiding technical jargon in favor of simple directions that make it useful to persons without electronics backgrounds. The author acknowledges the feedback he has received from "our do-it-yourself authors," so this monograph should be accepted as a pretested product—something that is fairly rare among such publications. Rehabilitators can, then, recommend it to their clients with confidence that they will find it useful not only as a self-help guide to assistive devices, but also as bibliotherapy.

Visual Devices for Deaf and Hard of Hearing People: State-of-the-Art. Judith E. Harkins. GRI Monograph Series A, No. 3. Washington, DC: Gallaudet Research Institute, Gallaudet University, 1991, 49 pp. Illustrated.
by Jerome D. Schein, Ph.D.

The author organizes the information about devices to aid visual communication for deaf and hard of hearing people around four areas: telecommunications, broadcast media, face-to-face, and environmental awareness. The contents of each section describe products, discuss applicable government policies, and present views of research and development at present and in the near future.

Leafing through the chapters, one is struck with the great progress made in the past quarter-century. No longer can one point to the iron of Alexander Graham Bell creating a giant economic barrier for deaf people as he attempted to develop a device to aid in their speech development. Adapted telephones (telephonic devices for the deaf or TDDs) now enable deaf persons to access the phone system, though there is still a distance to travel between here and quality.

Captioned television gives deaf people the opportunity to become 'couch potatoes'—a status formerly limited to those who could hear and see. One small omission in the text is any mention of the use of radio signals to transmit information in readable form, a technique whose feasibility was demonstrated nearly two decades ago.* If this procedure were revived, it would add substantially to the range of telecommunication for deaf persons.

Ways to facilitate proximal communication, such as devices to assist in lip-reading and those that convert speech to print, are being tested and refined. Their place in the future of communication for deaf persons is as yet not clear, since research often springs surprises. Of particular interest are approaches to speech-to-text conversion that do not require human mediation, as exemplified by *DragonDictate.* Such automatic translation opens intriguing vistas for the participation of a deaf person in meetings.

The use of lights and vibrators to signal changes in the environment have become numerous and varied. All of these developments have not reached the same stages of commercialization and consumer acceptability, but this monograph makes clear that further progress is a reasonable expectation for the days ahead.

The Gallaudet Research Institute is providing a significant service to the field by keeping it advised of advances in communication for deaf and hard of hearing people through the monograph series. Rehabilitators and educators should strive to keep informed about the Institute's numerous publications forthcoming in this area. Those fortunate enough to obtain the publication under review here will certainly be encouraged to seek out more like it.

Rehabilitation Engineering. Edited by R.V. Smith and J.H. Leslie, Jr. Boca Raton, FL: CRC Press, 1990, 548 pp.
by Franklyn K. Coombs, Director, Rehabilitation Research and Development Unit, VA Medical Center, Decatur, GA

The CRC *Rehabilitation Engineering* text is not the typical reference book one would expect from CRC. It is, as are many "state of the art" reviews, a collection of papers by professionals well-known in their specialized area of clinical service delivery. Unlike other reference books, this text does not contain the usual collection of charts and tables of data to solve well-defined problems. Instead, what is available to the reader is a collection of ideas describing how certain general situations are addressed. From these ideas, the person seeking information about "assistive technology" may gain valuable insight on how best to approach his/her own specific situation.

The text illustrates a typical problem in this field, which is, how many clients (or patients) need these services? The

*J.D. Schein and R. Hamilton. *Impact 1980: Telecommunications for Deaf People.* Silver Spring, MD: National Association of the Deaf, 1980.

introduction in Chapter 2, on the "numbers game," states (on page 15, last paragraph) that there are "about 400,000 people" (who use a wheelchair). However, the opening paragraph of Chapter 11 (page 195) states that there are "approximately 750,000 people" with disabilities that require the use of wheelchairs. This is almost a 100 percent difference in the "numbers game." It is neither the fault of the authors nor the editors that there is no better definition of the magnitude of the problem, or the need of the users. This is a problem with which all professionals in the field of rehabilitation must grapple.

The text is divided into four major sections: MEDICAL, EVALUATION, SPECIAL APPLICATIONS, and DEVICE ASSESSMENT. The SPECIAL APPLICATIONS section is subdivided into six smaller categories of *Independent Living, Communication, Seating and Mobility, Vocational, Transportation*, and *Recreation*. These sections present a fair overview of the spectrum of clinical rehabilitation engineering.

There could have been better organization of the chapters and the organization of the book. Specifically, Chapter 17, entitled "Rehabilitation Engineering Clinic," was placed under the *Recreation* category in SPECIAL APPLICATIONS. Considering that this is the theme of the text, one would have expected this to have a special place, or at least not be a subheading under *Recreation*. This was distressing because Chapter 17 was a very good review of the practice of clinical service delivery in rehabilitation engineering. In this line, Chapter 4, "Selection of Assistive Devices for Children," was out of place in the MEDICAL section. It may have been better placed following Chapter 20, which discussed the needs of children. Similarly, Chapter 16, entitled "Rehabilitation Assessment/Practice Demographics of Worker Disability" in the Table of Contents, was placed under the *Recreation* category in SPECIAL APPLICATIONS. However, in the text, it was only "Demographics of Worker Disability." This chapter may have been better placed after Chapter 2, which presented an overview of the disabled U.S. population.

The *Transportation* category consisted of one chapter of 118 pages in length. Considering that the other chapters presented an introduction or an overview of a specialty area, this chapter contained excessive detail. It may have been better served if had been shortened by the editors, with reference to other texts for detail of application. Much of this information may become outdated, which further supports the reduction in the numerous lists and forms.

Each of the chapters is worth reading by those in clinical practice, in spite of the criticism on organization. It may also serve as an introductory text for students in several different disciplines, who may be new to the field and could use the broader picture presented. The text, in general, is above average, and should be a useful reference for those in clinical practice.

Life in the Community: Case Studies of Organizations Supporting People with Disabilities. Edited by Steven J. Taylor, Robert Bogdan and Julie Ann Racino, Volume 1 in the Community Participation Series. Baltimore: Paul H. Brookes Publishing Co., 1991, 280 pp.

by Alexandra Enders, O.T.R., The Montana University Affiliated Rural Institute on Disabilities, University of Montana, Missoula, MT

The 15 very readable case studies which form the core of this book describe agencies and groups that are attempting to help people with developmental disabilities, including those with severe disabilities, to move into the community and become part of the community. Based on site visits conducted from 1985 to 1990, the pragmatic researchers document positive examples of community integration with a view toward identifying ideas, practices, and strategies that others can use to help people attain physical integration (e.g., community-based housing and coordinated support services), as well as social integration (becoming active participants in the community).

A reflection of the current state of the art, the emphasis is primarily on physical integration, and issues related to suitable housing situations; however, broader community integration issues are included, especially the challenges involved. Part 1 focuses on children with developmental disabilities and their families; Part 2 covers adults; and Part 3 puts community integration issues into the broader context of community and society.

The most interesting and broadly applicable parts of the book are the introductory chapter, section introductions, Preface, Foreword, and Conclusion. Here the authors and editors provide a framework and context for reviewing the case studies and for asking the right questions: they synthesize the characteristics of responsive organizations, and in Chapter 11, provide guidance for sustaining positive changes.

For people working in clearly defined areas such as assistive technology, this book provides a good overview of some of the real life struggles for integration facing people with disabilities in the community, and shows them where the technology fits in. This is a useful book for anyone interested in organizational analysis, especially in areas where human services are driven by social policies undergoing

rapid and profound changes. And for those working in community integration, it provides many thought-provoking examples of effective approaches to service, and the challenges that lie ahead.

Living with Low Vision: A Resource Guide for People with Sight Loss. Lexington, MA: Resources for Rehabilitation, 1990, 151 pp.

by William De l'Aune, Ph.D. and Bruce B. Blasch, Ph.D., Rehabilitation Research and Development Unit, VA Medical Center, Decatur, GA

The title promises and the book delivers an organized catalog of information about organizations and assistive devices that can assist individuals with impaired vision. Thoughtfully printed in 18 point bold type, the publication is organized into eleven chapters. Each chapter consists of introductory remarks about the topic, a listing of organizations capable of providing information or assistance, and an alphabetized register of relevant publications and/or assistive devices. Mailing addresses and prices are also included.

The topics covered by chapters are: Experiencing Vision Loss, Reading with Vision Loss, How to Keep Working with Vision Loss, High Tech Aids, Making Everyday Living Easier, Self-Help Groups, Services for Elders, Services for Children and Adolescents, Services for Veterans, Services for People with Vision Loss and Hearing Loss, and, Special Services and Products Listed by Eye Disease.

The major assumption underlying this book is that information in an accessible form will assist individuals in living with vision loss. This appears to be a very defensible point of view. Obvious efforts have been made to list some of the more obscure information about vision loss, while eliminating some of the complete and comprehensive sources. Because of this, there is a question if this is a professional presentation with errors of omission, or if it is a promotional piece for other materials from Resources for Rehabilitation. Two glaring examples include the omission or mention of the Association for Education and Rehabilitation of the Blind and Visually Impaired (AER), and the limited information about the American Foundation for the Blind (AFB). AER is the international organization of professionals serving individuals with a visual impairment. This organization has chapters in every state and province in the U.S. and Canada. The AFB publishes the *Directory of Services for Blind and Visually Impaired Persons in the United States* (the 23rd edition of this publication may be viewed as a competing publication). Also, this foundation has many services and resources including a toll-free hotline providing information on visual impairment, regional offices, and national consultants.

The organization of the material that is included is well handled. The narratives are rudimentary but appropriate in scope if this is simply to be used as a directory. However, at times the reader may feel that it is a do-it-yourself proscription of low vision aids or, for example, after reading an eleven-line section dealing with the topic of "Experiencing Vision Loss," the reader can correctly surmise that some of the more subtle points may not have been covered.

Perhaps the greatest challenge presented to a resource guide such as this is less the content, but the context in which it will be used. Access to information, no matter how accurate or complete, is necessary but not sufficient to negotiate the complex problems of vision loss. *Living with Low Vision* is a tool that provides minimal direct information on the topics covered (in some cases a "laundry list"), and access to further information. If used for this purpose, it may be a useful addition to the bookshelf of professionals and consumers. If it is used as a source of content information, it is far less adequate. The publisher has accomplished his stated objectives of preparing a resource guide. It is the responsibility of the reader to recognize and respect the inevitable limitations on detail imposed by this success, and therefore determine its true value.

PUBLICATIONS OF INTEREST

Compiled by Beryl M. Benjers, Ph.D.
Departments Editor

This list of references offers *Journal* readers significant information on the availability of recent rehabilitation literature in various scientific, engineering, and clinical fields. The *Journal* provides this service in an effort to fill the need for a comprehensive and interdisciplinary indexing source for rehabilitation literature.

All entries are numbered so that multidisciplinary publications may be cross-referenced. They are indicated as *See also* at the end of categories where applicable. A listing of the periodicals reviewed follows the references. In addition to the periodicals covered regularly, other publications will be included when determined to be of special interest to the rehabilitation community. To obtain reprints of a particular article or report, direct your request to the appropriate contact source listed in each citation.

Page **List of Categories**

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Contact: Robert L. Waters, MD, Rancho Los Amigos Medical Center, Downey, CA 90242

281. Results of Spinal Arthrodesis with Pedicle Screw-Plate Fixation. West JL III, et al., *J Bone Joint Surg* 73A(8):1179-1184, 1991.
Contact: James L. West, III, MD, PO Box 907000, Mobile, AL 36607

282. Screw Fixation of Odontoid Fractures and Nonunions. Esses SI, Bednar DA, *Spine* 16(10S):S483-S485, 1991.
Contact: Stephen I. Esses, MD, FRCSC, ECI-008 Toronto Western Hospital, 399 Bathurst St., Toronto, Ontario M5T 2S8, Canada

283. Semen Retrieval in Spinal Cord Injured Men. Rawicki HB, Hill S, *Paraplegia* 29(7):443-446, 1991.
Contact: H. B. Rawicki, MB, BS, FACRM, Director Spinal Rehabilitation, Caulfield General Medical Centre, 260-294 Kooyong Rd., Caulfield 3162, Victoria, Australia

284. Spinal Cord Injury Syndrome with Motor Sparing in the Absence of All Sensation. Kowalske KL, et al., *Arch Phys Med Rehabil* 72(11):932-934, 1991.
Contact: Karen J. Kowalske, MD, Dept. of PM&R, 5323 Harry Hines Blvd., Dallas, TX 75235-9055

285. Strength and Kinematic Responses of Dynamic Cervical Spine Injuries. Yoganandan N, et al., *Spine* 16(10S):S511-S517, 1991.
Contact: Narayan Yoganandan, PhD, Dept. Neurosurgery, Medical College of Wisconsin, 9200 West Wisconsin Ave., Milwaukee, WI 53226

286. Survivorship Analysis of Pedicle Spinal Instrumentation. McAfee PC, Weiland DJ, Carlow JJ, *Spine* 16(8):S422-427, 1991.
Contact: Paul C. McAfee, MD, Orthopaedic Associates, PA, 1217 St. Paul St., Baltimore, MD 21202

287. Survivorship Analysis of VSP Spine Instrumentation in the Treatment of Thoracolumbar and Lumbar Burst Fractures. Ebelke DK, et al., *Spine* 16(8S): S428-S432, 1991.
Contact: David K. Ebelke, MD, 2750 Clay Edwards Dr., Suite 600, Kansas City, KS 64116

288. Toward a Health Services Research Capacity in Spinal Cord Injury. DeJong G, Batavia AI, *Paraplegia* 29(6):373-389, 1991.
Contact: G. DeJong, PhD, National Rehabilitation Hospital Research Center, Dept. of Community and Family Medicine, Georgetown University School of Medicine, Washington, DC 20057

289. Understanding and Treating Motivation Difficulties in Ventilator-Dependent SCI Patients. Jordan SA, et al., *Paraplegia* 29(7):431-442, 1991.
Contact: S. A. Jordan, PhD, Dept. of Psychology, Madonna Centres, 5401 South St., Lincoln, NE 68506-2134

290. The Use of Sublaminar Cables to Replace Luque Wires. Songer MN, et al., *Spine* 16(8S):S418-S421, 1991.
Contact: Matthew N. Songer, MD, 1414 West Fair Ave., Suite 149, Marquette, MI 49855

291. Using Tissue Expanders in Spinal Surgery for Deficient Soft Tissue or Postirradiation Cases. Paonessa KJ, et al., *Spine* 16(8S):S324-S327, 1991.
Contact: Kenneth J. Paonessa, MD, Norwich Orthopaedic Group, 2 Clinic Dr., Norwich, CT 06360

292. The Value of Magnetic Resonance Imaging (MRI) in the Follow-up Management of Spinal Injury. Sett P, Crockard HA, *Paraplegia* 29(6):396-410, 1991.
Contact: P. Sett, MS, FRCS (SN), The National Hospitals for Nervous Diseases, Maida Vale, London W9 1TL, UK

See also 14, 17, 24, 26, 28, 29, 31, 34, 45, 51, 68, 70, 124, 136, 193, 196, 198, 200, 302

VOCATIONAL

293. Employment Survival Skills: Frequency and Seriousness of Skill Deficit Occurrences for Job Loss. Mueller HH, Wilgosh L, *Can J Rehabil* 4(4):213-228, 1991.
Contact: Horst H. Mueller, PhD, Psychology Dept., Glenrose Rehabilitation Hospital, 10230 111th Ave., Edmonton, Alberta T5G 0B7, Canada

294. Models of Vocational Rehabilitation (Seven articles). Webman PH, Kreutzer JS (Guest Eds.), *J Head Trauma Rehabil* 6(3):1-84, 1991.
Contact: (See journal for individual articles.) *The Journal of Head Trauma Rehabilitation*, 7201 McKinney Circle, Frederick, MD 21701

295. Open Minds Will Open Doors. *Paraplegia News* 45(10):31-37, 1991.
Contact: Paraplegia News, 5201 North 19th Ave., Suite 111, Phoenix, AZ 85015-2994

296. The "Open Road" Project: Real Jobs for People with Mental Handicap. Walsh PN, Rafferty M, Lynch C, *Int J Rehabil Res* 14(2):155-161, 1991.
Contact: Patricia N. Walsh, St. Michael's House Research, Upper Kilmacud Rd., Stillorgan, Co. Dublin, Ireland

297. The Vocational Ability Quotient System: A New Approach in Predicting Vocational Rehabilitation Potential. Wallace GCM, Carlin RM, Nordin DM, *Can J Rehabil* 4(4):239-245, 1991.
Contact: Gordon C.M. Wallace, MA, The Vocational Consulting Group, Inc., Suite 660, 1665 West Broadway, Vancouver, BC, V6J 1X1, Canada

WHEELCHAIRS and POWERED VEHICLES

298. Predication of Ramp Traversability for Wheelchair Dependent Individuals. Cappozzo A, et al., *Paraplegia* 29(7):470-478, 1991.
Contact: A. Cappozzo, Institute of Human Physiology, Faculty of Medicine and Surgery, Rome University, La Sapienza, Italy

299. Ramp Length/Grade Prescriptions for Wheelchair Dependent Individuals. Canale I, et al., *Paraplegia* 29(7):479-485, 1991.
Contact: I. Canale, Center for Neuromotor Rehabilitation, Santa Lucia Clinic, via Ardeatina 306, 00179 Rome, Italy

See Also 200

WOUNDS and ULCERS

300. Four Types of Venous Flaps for Wound Coverage: A Clinical Appraisal. Chen H-C, Tang YB, Samuel Noordhoff M, *J Trauma* 31(9):1286-1293, 1991.
Contact: Hung-chi Chen, MD, FACS, 6F-1, 28, Hang-chow North Rd., Taipei, Taiwan

301. Neuromuscular Complications Following Electrical Injury—Incidence and Special Problems in Rehabilitation. Varghese G, Mani MM, Redford JB, *Clin Rehabil* 5(3):195-200, 1991.
Contact: Prof. George Varghese, Dept. of Rehabilitation Medicine, University of Kansas Medical Center, 39th and Rainbow Blvd., Kansas City, KS 66103

302. Pressure Sore Carcinoma: A Late but Fulminant Complication of Pressure Sores in Spinal Cord Injury Patients: Case Reports. Dumurgier C, et al., *Paraplegia* 29(6):390-395, 1991.
Contact: C. Dumurgier, Chirurgien en Chef, Service de Chirurgie et de Paraplegies Traumatiques, Institution Nationale des Invalides, Paris 75007, France

See Also 59, 257, 268

Periodicals reviewed for PUBLICATIONS OF INTEREST

Accent on Living
Acta Orthopaedica Scandinavica
Advances in Orthopaedic Surgery
American Annals of the Deaf
American Journal of Occupational Therapy
American Journal of Physical Medicine and Rehabilitation
American Journal of Sports Medicine
American Rehabilitation
Annals of Biomedical Engineering
AOPA Almanac (American Orthotic and Prosthetic Association)
Applied Optics
Archives of Physical Medicine and Rehabilitation
ASHA (American Speech and Hearing Association)
Bio Engineering
Biomaterials, Artificial Cells and Artificial Organs
Biomedical Instrumentation & Technology
British Journal of Occupational Therapy
Caliper (Canadian Paraplegic Association)
Canadian Journal of Occupational Therapy
Canadian Journal of Rehabilitation
Clinical Biomechanics
Clinical Kinesiology
Clinical Orthopaedics and Related Research
Clinical Physics and Physiological Measurement

Clinical Rehabilitation
Communication Outlook
Computer Disability News
CRC Critical Reviews in Biomedical Engineering
DAV Magazine (Disabled American Veterans)
Discover
Electromyography and Clinical Neurophysiology
Electronic Design
Electronic Engineering
Electronics
Ergonomics
Harvard Medical School Newsletter
Headlines: The Brain Injury Magazine
Hearing Journal
Hearing Research
Human Factors: The Journal of the Human Factors Society
IEEE Engineering in Medicine and Biology Magazine
IEEE Transactions in Biomedical Engineering
IEEE Transactions in Systems, Man and Cybernetics
International Disability Studies
International Journal of Rehabilitation Research
International Journal of Technology & Aging
JAMA
Journal of Acoustical Society of America
Journal of American Optometric Association
Journal of Association of Persons with Severe Handicaps
Journal of Biomechanical Engineering
Journal of Biomechanics
Journal of Biomedical Engineering
Journal of Biomedical Materials Research
Journal of Bone and Joint Surgery—American Ed.
Journal of Bone and Joint Surgery—British Ed.
Journal of Clinical Engineering
Journal of Head Trauma and Rehabilitation
Journal of Medical Engineering and Technology
Journal of Neurologic Rehabilitation
Journal of Optical Society of America A
Journal of Orthopaedic and Sports Physical Therapy
Journal of Orthopaedic Research
Journal of Prosthetics and Orthotics
Journal of Rehabilitation
Journal of Rehabilitation Sciences
Journal of Speech and Hearing Research
Journal of Vision Rehabilitation
Journal of Visual Impairment and Blindness
Laser Focus World
Mayo Clinic Proceedings
Medical and Biological Engineering and Computing
Medical Device and Diagnostic Industry
Medical Electronics
Medical Physics
Medical Progress Through Technology
Medical Psychotherapy Yearbook
Medicine & Science in Sports and Exercise
Military Medicine
New England Journal of Medicine
The Occupational Therapy Journal of Research
Optometry and Vision Science
Orthopaedic Review
Orthopedic Clinics of North America
Orthopedics
Palaestra
Paraplegia
Paraplegia News
Physical and Occupational Therapy in Geriatrics
Physical Medicine and Rehabilitation
Physical Therapy
Physics Today
Physiotherapy
Proceedings of the Institution of Mechanical Engineers—Part H: Journal of Engineering in Medicine
Rehab Management
Rehabilitation Digest
Rehabilitation World
Robotics World
Scandinavian Journal of Rehabilitation Medicine
Science
Science News
Scientific American
SOMA: Engineering for the Human Body
Speech Technology
Spine
Sports 'N Spokes
Technical Aid to the Disabled Journal
Techniques in Orthopaedics
Topics in Geriatric Rehabilitation
VA Practitioner
Vanguard
Volta Review
Worklife

CALENDAR OF EVENTS

Compiled by Beryl M. Benjers, Ph.D.
Departments Editor

NOTE: An asterisk at the end of a citation indicates a new entry to the calendar.

1992

February 2-5, 1992
First International Conference on Long-Term Care Case Management Issues, Sponsored by the Washington Association of Area Agencies on Aging, Seattle, WA
Contact: Washington Association of Area Agencies on Aging, 618 Second Ave., Suite 250, Seattle, WA 98104-2217; (206) 684-0500*

February 7-8, 1992
Surgery of the Arm in Tetraplegia, Montpellier, France
Contact: C. Gilbert, Centre Propara, 263, Rue du Caducee, Parc Euromedecine, F-34090 Montpellier, France; Tel 67 04 67 04, Fax 47 61 95 20*

February 13-16, 1992
Association of Academic Physiatrists (AAP), Annual Spring Meeting, Orlando, FL
Contact: Carolyn L. Braddom, EdD, AAP, Box 977, 7100 Lakewood Bldg., Suite 112, Indianapolis, IN 46220*

February 14, 1992
Materials Research in Maxillofacial Prosthetics, Conference, Chicago, IL
Contact: Drs. Lawrence Gettleman and Zafrulla Khan, University of Louisville School of Dentistry, Louisville, KY 40292; (502) 588-5045, (800) 334-8635 Ext 5045*

February 14-17, 1992
American Association for Geriatric Psychiatry, San Francisco, CA
Contact: American Association for Geriatric Psychiatry, PO Box 376-A, Greenbelt, MD 20770*

February 17-21, 1992
MRI Update 1992: MR Angiography and Imaging of the Head, Spine and Musculoskeletal System, Tucson, AZ
Contact: Marti Carter, Course Coordinator, Continuing Medical Education, Inc., 11011 W. North Ave., Milwaukee, WI 53226; (414) 771- 9520*

February 20-25, 1992
American Academy of Orthopaedic Surgeons (AAOS), Annual Meeting, Washington, DC
Contact: AAOS, (312) 823-7186

February 23-28, 1992
Medical Imaging VI, Newport Beach, CA
Contact: SPIE—The International Society for Optical Engineering, PO Box 10, Bellingham, WA 98227-0010*

March 2-6, 1992
Musculoskeletal Imaging for Orthopaedic Surgeons and General Radiologists, St. Thomas, Virgin Islands
Contact: Continuing Medical Education, Boston University School of Medicine, 80 East Concord St., Boston, MA 02118; (617) 638-4605*

March 5-7, 1992
REHABILITATION: Science, Technology, Quality and Costs—Present and Future, La Jolla, CA
Contact: Meeting Management-Rehabilitation, 5665 Oberlin Dr., Suite 110, San Diego, CA 92121; (619) 453-6222, Fax (619) 535-3880*

March 6-7, 1992
American Orthotic and Prosthetic Association (AOPA), Region IV Meeting, Raleigh, NC
Contact: Dan Ferguson, CPO, (919) 966-4630

March 8-11, 1992
American Institute of Ultrasound in Medicine (AIUM), 36th Annual Meeting, San Diego, CA

Contact: AIUM, 11200 Rockville Pike, Suite 205, Rockville, MD 20852-8139*

March 13-16, 1992
American Society on Aging, San Diego, CA
Contact: American Society on Aging, 833 Market St., Suite 512, San Francisco, CA 94103

March 18-21, 1992
Technology and Persons with Disabilities, Los Angeles, CA
Contact: Dr. Harry J. Murphy, Office of Disabled Student Services, California State University at Northridge, 18111 Nordhoff St. - DVSS, Northridge, CA 91330; (818) 885-2578, Fax (818) 885-4929*

March 20-21, 1992
Florida Association of Orthotists and Prosthetists, Annual Meeting and Scientific Symposium, Miami, FL
Contact: AAOP, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7118

March 21-25, 1992
Deaf-Blind Services in the '90s: Revitalization and Future Directions, Washington, DC
Contact: Marianne Riggio, Perkins School for the Blind, 175 North Beacon St., Watertown, MA 02172; (617)924-3434, Ext 264*

March 28-April 1, 1992
American Occupational Therapy Association (AOTA), Annual Meeting, Houston, TX
Contact: AOTA, 1383 Piccard Dr., Suite 300, Rockville Pike, Rockville, MD 20850*

April 1-4, 1992
American Burn Association Annual Meeting, Salt Lake City, UT
*Contact:*Baltimore Regional Burn Center, 4940 Eastern Ave., Baltimore, MD 21224*

April 5-9, 1992
Biomedical Engineering Society (BES), Annual Meeting, Anaheim, CA
Contact: BES, PO Box 2399, Culver City, CA 90231

April 7-12, 1992
American Orthotic and Prosthetic Association (AOPA), Region IV Meeting, Miami, FL
Contact: Dan Ferguson, CPO, (919) 966-4630*

April 12-16, 1992
American Association of Neurological Surgeons (AANS), Annual Meeting, San Francisco, CA
Contact: AANS, 22 South Washington St., Suite 100, Park Ridge, IL 60068*

April 18, 1992
Basic Flex-Foot® Course, Pittsburgh, PA
Contact: Marcia Fosberg, (800) 233-6263 or (800) 843-7065 in California*

April 22-25, 1992
Independence 1992: International Congress and Exposition on Disability, "Independence: Self-Determination by Persons with Disabilities," Vancouver, BC, Canada
Contact: B.C. Pavillon Corp., Suite 200, 1190 Melville St., Vancouver, BC, V6E 3W1, Canada; (604) 689-5084, Fax (604) 689-4806, TDD (604) 691- 2628

April 23-26, 1992
Arthroscopy Association of North America (AANA), 11th Annual Meeting, Boston, MA
Contact: AANA, 2250 E. Devon Ave., Suite 101, Des Plaines, IL 60018; (708) 299-9444*

April 23-26, 1992
Wound Healing Society, 2nd Annual Meeting, Richmond, VA
Contact: Dr. R.F. Diegelmann, Wound Healing Center, Medical College of Virginia, Box 117, MCV Station, Richmond, VA 23298-0117*

April 29-May 2, 1992
National Council on Aging, Annual Meeting, Washington, DC
Contact: National Council on Aging, 600 Maryland Ave. SW, West Wing 100, Washington, DC 20024

April 30-May 2, 1992
Second Annual Educational Conference of the JMA Foundation, Inc., and the National Brain Injury Research Foundation (NBIRF), Baltimore, MD
Contact: JMA Foundation, Inc., 1730 M St. NW, Suite 903, Washington, DC 20036

May 2-9, 1992
American Academy of Neurology (AAN), Annual Meeting, San Diego, CA
Contact: AAN, 2221 University Ave. SE, Suite 335, Minneapolis, MN 55414*

May 6-9, 1992
American Trauma Society (ATS), Annual Meeting, Washington, DC
Contact: ATS, 1400 Mercantile Lane, Suite 188, Landover, MD 20785*

May 7-10, 1992
American Board of Physical Medicine and Rehabilitation, Annual Meeting, Rochester, MN
Contact: American Board of Physical Medicine and Rehabilitation, Suite 674, Northwest Center, 21 First St. SW, Rochester, MN 55902

May 11-15, 1992
Acoustical Society of America (ASA), 123rd Semi-Annual Meeting, Salt Lake City, UT
Contact: ASA, 335 East 45th St., New York, NY 10017

May 12-14, 1992
International Scientific Conference on Prevention of Work-Related Musculoskeletal Disorders, Stockholm, Sweden
Contact: Ms. Gun Carlsson, National Institute of Occupational Health, S-171 84 Solna, Sweden*

May 13-15, 1992
5th International Congress on Ambulatory Monitoring, St. Louis, MO
Contact: 5th International Congress on Ambulatory Monitoring, PO Box 11845, St. Louis, MO 63105*

May 14-16, 1992
American Orthotic and Prosthetic Association (AOPA), Region V Annual Meeting, Kings Island, OH
Contact: AOPA, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7116

May 15-17, 1992
American Spinal Injury Association, Annual Meeting, Toronto, Ontario, Canada
Contact: American Spinal Injury Association, 2020 Peachtree Rd. NW, Atlanta, GA 30309

May 16-19, 1992
American College of Medical Physics (ACMP), Ninth Annual Meeting, Lake of the Ozarks, MO
Contact: ACMP, 1819 Preston White Dr., Reston, VA 22091

May 17-20, 1992
American Association of Plastic Surgeons (AAPS), Annual Meeting, Vancouver, Canada
Contact: AAPS, 10666 North Torrey Pines Rd., La Jolla, CA 92037*

May 17-20, 1992
International Trauma Congress, Berlin, Germany
Contact: The Congress Secretariat, 5 Alfred Rd., Farnham, Surrey GU9 8ND, England; Tel +44 44 252 735286, Fax +44 252 737634*

May 18-19, 1992
European Conference on Joint Replacement in the 1990s, East Midlands Conference Centre, Nottingham, UK
Contact: Alison Elgar, Institution of Mechanical Engineers, 1 Birdcage Walk, London SW1H 9JJ, UK; Tel 071 973 1281*

May 21-24, 1992
Meeting of the International Society for the Study of the Lumbar Spine, Chicago, IL
Contact: Prof. Alf Nachemson, Dept. of Orthopaedics, Sahlgren Hospital, S-413 45, Goteborg, Sweden; Tel +46 31 601000

May 23-27, 1992
XIth International Symposium on Posture and Gait: Control Mechanisms, Portland, OR
Contact: Posture and Gait Symposium Coordinator, Good Samaritan Hospital and Medical Center, 1015 N.W. 22nd Ave., N300, Portland, OR 97210-5198; (503) 229-7348, Fax (503) 790-1201*

May 30-June 3, 1992
Association for the Advancement of Medical Instrumentation (AAMI), 27th Annual Meeting, Anaheim, CA
Contact: AAMI, 3330 Washington Blvd., Suite 400, Arlington, VA 22201-9985; (703) 525-4890*

May 31-June 4, 1992
Third International Conference on Physical Activity, Aging and Sports (PAAS- III), Jyvaskyla, Finland
Contact: Sara Harris, Center for the Study of Aging, 706 Madison Ave., Albany, NY 12208 or Prof. Eino Heikkinen, Dept. of Health Sciences, University of Jyvaskyla, SF 40100 Jyvaskyla, Finland*

May 31-June 5, 1992
American Society of Neuroradiology, Annual Meeting, St. Louis, MO
Contact: American Society of Neuroradiology, 1415 West 22nd St., Tower B, Oak Brook, Il 60521*

June 2- 5, 1992
Fifth International Symposium on Spinal Cord Monitoring (ISSCM), London, England
Contact: Symposium Secretariat, Conference Associates and Service Ltd., ISSCM, Congress House, 55 New Cavendish St., London WIM 7RE, UK; Tel 071 486 0531, Fax 071 935 7559*

June 3-5, 1992
Scandinavian Orthopedic Association, 46th Congress, Malmo, Sweden
Contact: Congress Bureau, ICM AB, Geijersgatan 50, S-216 19 Malmo, Sweden; Tel +46 40 16 26 00, Fax +46 40 15 74 80*

June 3-6, 1992
American Orthotic and Prosthetic Association (AOPA), Region II and III Meeting, Atlantic City, NJ
Contact: Gene DeMarco, (718) 237-0844*

June 7-10, 1992
RESNA Rehabilitation Technology, 15th Annual Conference, Toronto, Ontario, Canada
Contact: RESNA, Association for the Advancement of Rehabilitation Technologies, Suite 700, 1101 Connecticut Ave. NW, Washington, DC 20036; (202) 857-1199

June 7-10, 1992
18th Conference of the Canadian Medical and Biological Engineering Society (CMBEC), in Conjunction with the Annual RESNA Conference, Toronto, Ontario, Canada
Contact: CMBEC Secretariat, c/o National Research Council, Room 305, Bldg. M-50, Ottawa, Ontario K1A 0R8, Canada; (613) 993-1686, Fax (613) 954-2216

June 8-13, 1992
European Intensive Course on Digital Imaging Processing Applied to Orthopaedic and Dental Implants, Portugal
Contact: Prof. M.A. Barbosa, Dept. of Metallurgy, Faculty of Engineering, University of Porto, R. dos Bragas, 4099 Porto Codex, Portugal; Tel 351-2-2009297, Fax 351-2-319280

June 14-18, 1992
1992 American Physical Therapy Association (APTA), Annual Conference, Denver, CO
Contact: APTA, 1111 N. Fairfax St., Alexandria, VA 22314-1488*

June 21-22, 1992
European Spinal Deformities Societies Meeting, Lyon, France
Contact: Eric Bancilhon, 29, Rue President Ed. Herriot, 69002 Lyon, France

June 21-24, 1992
European Society for Biomechanics (ESB), Rome, Italy
Contact: ESB'92 Conference Secretariat, Instituto di Fisiologia Umana, Universita La Sapienza, Piazzale Aldo Moro 5, 00185 Rome, Italy

June 22-26, 1992
American Society for Hospital Engineering (ASHE), Annual Conference and Exhibition, Nashville, TN
Contact: ASHE, PO Box 92258, Chicago, IL 60675-2258*

June 24-26, 1992
Second International Congress of Movement Disorders, Munich, Germany
Contact: Secretariat ISMD, PO Box CH-4005, Basel, Switzerland*

June 24-27, 1992
Cervical Spine Research Society, Third Common Meeting (American and European Sections), Athens, Greece
Contact: Dem. S. Korres, 10 Heyden St., 104 34 Athens, Greece*

June 27-July 1, 1992
International Meeting—Low Back Pain, Aalborg, Denmark
Contact: Aalborg Kongres Bureau, Ostera 8, DK 9000 Aalborg, Denmark; Tel +45 98 12 63 55, Fax +45 98 16 69 22*

June 28-July 2, 1992
Ninth International Congress of The International Society of Electrophysiological Kinesiology (ISEK), Florence, Italy
Contact: Organizing Secretariat, CE.S.P.RI., Fondazione Pro Juventute, Don Carlo Gnocchi, Via Imprunetana 124-50020 Monte Oriolo, Florence, Italy; Tel 39 55 208322/208426, Fax 39 55 208428*

June 28-July 2, 1992
Seventh World Conference on Titanium, San Diego, CA
Contact: Barbara J. Kamperman, The Minerals, Metals and Materials Society, 420 Commonwealth Dr., Warrendale, PA 15086; (412) 776-9050*

June 28-July 3, 1992
International Society for Prosthetics and Orthotics (ISPO), Seventh World Congress, Chicago, IL
Contact: Seventh World Congress of ISPO, Moorevents, Inc., 400 N. Michigan Ave., Suite 2300, Chicago, IL 60611; (312) 644-5997

June 29-30, 1992
National Association of Rehabilitation Facilities, Annual Meeting, Chicago, IL
Contact: National Association of Rehabilitation Facilities, PO Drawer 17675, Washington, DC 20041

June 30-July 3, 1992
Canadian Association of Occupational Therapists (CAOT), Atlantic Conference '92, St. John's, Newfoundland, Canada
Contact: CAOT, 110 Eglinton Avenue West, Third Floor, Toronto, Ontario M4R 1A3, Canada; (416) 487-5404

July 5-10, 1992
VIth Mediterranean Conference on Medical and Biological Engineering, Capri, Italy
Contact: Prof. M Bracale, Cattedra di Electronica Biomedica, Via Claudio 21, 80125 Napoli, Italy

July 12-15, 1992
Shoulder Surgery, Fifth International Conference, Paris, France
Contact: Convergences-V^e. ICSS, 120, avenue Gambetta, 75020 Paris, France; Fax +33 1 40 31 01 65

July 19-24, 1992
International Arthroscopy Congress, Platja d'Aro, Spain
Contact: Ramon Cugat, MD, C.H.A.T., Paseo de Gracia, II. 08007, Barcelona, Spain; Tel 34 3 301 6500, Fax 34 3 302 0243

July 22-24, 1992
International Sports Medicine Symposium, Pamplona, Spain
Contact: Jennifer Ulrich, Cleveland Clinic International Center, KK40, 9500 Euclid Ave., Cleveland, OH 44195-5125, (216) 444- 6737*

July 25, 1992
Basic Flex-Foot® Course, Memphis, TN
Contact: Marcia Fosberg, (800) 233-6263 or (800) 843-7065 in California*

July 28-31, 1992
Canadian Association of Prosthetists and Orthotists (CAPO), Convention, Edmonton, Alberta, Canada
Contact: 1992 CAPO Convention Office, (403) 451-4990

August 5-8, 1992
American Orthotic and Prosthetic Association (AOPA), Quad Regional Meeting, C'oeur D'Alene, ID
Contact: Jack Meredith, CO, (509) 326-6401

August 6-7, 1992
Workshop on Lumbar Pedicle Screw Fixation, Adelaide, South Australia
Contact: Robert D. Fraser, MB, BS, MD, FRACS, C/-Spinal Unit, Royal Adelaide Hospital, North Terrace, Adelaide, South Australia 5000*

August 9-14, 1992
4th International Congress of the Hard of Hearing, Jerusalem, Israel
Contact: Secretariat, PO Box 50006, Tel Aviv 61500, Israel; Tel 972 3 654571, Telex 341171, Fax 972 3 655674

August 17-20, 1992
Second World Congress on Myofascial Pain and Fibromyalgia, Copenhagen, Denmark
Contact: Danish Rheumatism Association, Gigtforeningen, Hauchsvej 14, DK-1825 Frederiksberg C, Denmark*

August 23-27, 1992
American Association of Physicists in Medicine (AAPM), 34th Annual Meeting with the Division of Medical and Biological Physics of the Canadian Association of Physicists, Calgary, Alberta, Canada
Contact: AAPM, 335 East 45th St., New York, NY 10017; (212) 661-9404

September 4-5, 1992
Technology Transfer between High Tech Engineering and Biomechanics, International Conference on Experimental Mechanics, Limerick, Ireland
Contact: The Conference Secretariat (BSSM '92), Dept. of Mechanical and Production Engineering, University of Limerick, Plassey Technological Park, Limerick, Ireland; Tel +353-61-333644, Fax 353-61-330316, Telex 500 70609

September 6-10, 1992
MEDINFO '92: 7th World Congress on Medical Informatics, Geneva, Switzerland

Contact: Symporg SA, 108 Route de Frontenex, CH-1208, Geneva, Switzerland*

September 6-11, 1992
Interdisciplinary Perspectives in Speech-Language Pathology, Dublin, Ireland
Contact: Paulene McKeever, Conference Management Services, 26 Temple Lane, Dublin 2, Ireland

September 7-11, 1992
17th World Congress of Rehabilitation International: Accelerating Efforts to Equalization of Opportunities—Strategies for the 90s, Nairobi, Kenya
Contact: The Association for the Physically Disabled of Kenya Headquarters, Lagos Rd., PO Box 46747, Nairobi, Kenya; Tel 24443 and 332227

September 9-11, 1992
Institute of Physical Sciences in Medicine (IPSM), Annual Conference, Lincoln, UK
Contact: General Secretary, IPSM, 4 Campleshon Rd., York YO1 1PE, UK

September 14-18, 1992
XIth World Congress of the International Federation of Physical Medicine and Rehabilitation, Dresden, Germany
Contact: Prof. Jurgen Kleditsch, Dept. of Physical Therapy and Research, Clinic of Orthopaedics, Medical Academy "Carl Gustav Carus," Dresden, GDR-8019

September 17-19, 1992
American Association for the Surgery of Trauma, Annual Meeting, Louisville, KY
Contact: Dr. Cleon Goodwin, NY Cornell Medical Center, 525 East 68th St., L706, New York, NY 10021*

September 20-24, 1992
Audiology in Europe—The British Society of Audiology (BSA), Four-Yearly Conference, Cambridge, UK
Contact: BSA, 80 Brighton Rd., Reading RG6 1PS, UK

October 17, 1992
Basic Flex-Foot® Course, Vancouver, Canada
Contact: Marcia Fosberg, (800) 233-6263 or (800) 843-7065 in California*

October 17-21, 1992
American Health Care Association, Annual Meeting, San Francisco, CA
Contact: American Health Care Association, 120 L St. NW, Washington, DC 20005*

October 26-31, 1992
American Orthotic and Prosthetic Association (AOPA), Annual National Assembly, Orlando, FL
Contact: Annette Suriani, AOPA, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7116

October 27-31, 1992
6th European Congress on Intensive Care Medicine, Barcelona, Spain
Contact: Inter-Congress, Gran Via Corts Catalanes 646, SP-08007, Spain*

October 29-November 1, 1992
14th Annual International Conference of the IEEE EMBS, Paris, France
Contact: Swamy Laxminarayan, Academic Computing Center, MSB-A539, NJ Medical School, 185 South Orange Ave., Newark, NJ 07103, or Jean Louis Coatrieux, Lab Traitement du Signal, Universite de Rennes I, Campus de Beaulieu, Rennes Cedex, France

October 29- November 1, 1992
Speech Communication Association (SCA), Annual Meeting, Chicago, IL
Contact: SCA, James L. Gaudino, Exec. Dir., 51505 Blacklick Rd., Bldg. E, Annandale, VA 22003*

November 1-6, 1992
International Congress on Rehabilitation in Psychiatry, 5th Congress, Jerusalem, Israel
Contact: Secretariat, PO Box 50006, Tel Aviv 61500,Israel*

November 7-10, 1992
American Pain Society, Annual Meeting, New Orleans, LA
Contact: American Pain Society, 5700 Old Orchard Rd., 1st Fl., Skokie, IL 60077-1024

November 8-11, 1992
16th Symposium on Computer Applications in Medical Care (SCAMC), Baltimore, MD
Contact: The George Washington University Medical Center, Office of Continuing Education, 2300 K St. NW, Washington, DC 20037

November 8-13, 1992
American Academy of Physical Medicine and Rehabilitation, Annual Meeting, San Francisco, CA

Contact: American Academy of Physical Medicine and Rehabilitation, 122 South Michigan Ave., Suite 1300, Chicago, IL 60603*

November 15-18, 1992
American Geriatrics Society (AGS), Annual Meeting, Washington, DC
Contact: AGS, Suite 400, 770 Lexington Ave., New York, NY 10021*

November 20-23, 1992
American Speech-Language-Hearing Association (ASHA), Annual Convention, San Antonio, TX
Contact: ASHA, 10801 Rockville Pike, Rockville, MD 20852; (301) 897-5700

November 29-December 4, 1992
Joint Meeting of the American Association of Physicists in Medicine (AAPM) with the Radiological Society of North America (RSNA), Chicago, IL
Contact: AAPM, 335 East 45th St., New York, NY 10017; (212) 661-9404

December 2-4, 1992
7th International Conference on Biomedical Engineering (ICBME), Singapore
Contact: The Secretary, 7th ICBME 1992, Dept. of Orthopaedic Surgery, National University Hospital, 5 Lower Kent Ridge Rd., Singapore 0511, Republic of Singapore; Tel 7724424, Telex RS 55503 NUH, Fax 7780720*

1993

February 18-23, 1993
American Academy of Orthopaedic Surgeons (AAOS), Annual Meeting, San Francisco, CA
Contact: AAOS, (312) 823-7186

March 30-April 4, 1993
American Academy of Orthotists and Prosthetists (AAOP), Annual Meeting and Scientific Symposium, Las Vegas, NV
Contact: AAOP, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7118

April 4-8, 1993
XIIIth World Congress on Occupational Safety and Health, New Delhi, India
Contact: XIIIth World Congress on Occupational Safety and Health, c/o National Safety Council , PO Box 26754, Sion, Bombay 400 022, India; Tel 407- 3285, 407-3694, 409-1285, Fax +91-22-525-657, Telex 011-74577 CLI-IN. Cable: NASACIL*

May 8-12, 1993
Association for the Advancement of Medical Instrumentation (AAMI), 28th Annual Meeting, Boston, MA
Contact: AAMI, 3330 Washington Blvd., Suite 400, Arlington, VA 22201; (703) 525-4890*

June 10-12, 1993
7th Congress of the European Society for Shoulder and Elbow Surgery, Aarhus, Denmark
Contact: Orthopaedic Hospital, Randersvej 1, DK-8200 Aarhus N. Denmark; Tel +45 86 16 75 00 Ext 4622, Fax +45 86 10 77 33

August 8-12, 1993
35th Annual Meeting of the American Association of Physicists in Medicine (AAPM), Washington, DC
Contact: AAPM, 335 East 45th St., New York, NY 10017; (212) 661-9404

October 12-16, 1993
American Orthotic and Prosthetic Association (AOPA), Annual National Assembly, Reno, NV
Contact: Annette Suriani, AOPA, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7116*

October 12-17, 1993
8th Congress of the European Federation of Societies for Ultrasound in Medicine and Biology, Innsbruck, Austria
Contact: Kongresshaus Innsbruck, PO Box 533, A-6021 Innsbruck, Austria

October 17-22, 1993
Xth International Congress of Neurological Surgery, Acapulco, Mexico
Contact: Fernando Rueda-Franco, MD, PO Box 101-88, Col. Insurgentes Cuicuilco Deleg. Coyoacan Mexico, DF 04530, Mexico; Fax 905 264 2563*

October 25-30, 1993
American Orthotic and Prosthetic Association (AOPA), Annual National Assembly, Reno, NV
Contact: Annette Suriani, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7116

October 30-November 3, 1993
17th Symposium on Computer Application in Medical Care (SCAMC), Baltimore, MD
Contact: The George Washington University Medical Center, Office of Continuing Education, 2300 K St. NW, Washington, DC 20037; (202) 994-8928

November 19-22, 1993
American Speech-Language-Hearing Association (ASHA) Annual Convention, Anaheim, CA
Contact: ASHA, 10801 Rockville Pike, Rockville, MD 20852; (301) 897-5700

November 28-December 3, 1993
Joint Meeting of the American Association of Physicists in Medicine (AAPM) with the Radiological Society of North America (RSNA), Chicago, IL
Contact: AAPM, 335 East 45th St., New York, NY 10017; (212) 661-9404

1994

March 15-20, 1994
American Academy of Orthotists and Prosthetists (AAOP), Annual Meeting and Scientific Symposium, Nashville, TN
Contact: Annette Suriani, AAOP, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7118*

April 9-16, 1994
IRMA VII—Seventh World Congress of the International Rehabilitation Medicine Association: 25th Anniversary of IRMA, Washington, DC
Contact: IRMA VII, 875 Kings Hwy., West Deptford, NJ 08096

July 17-21, 1994
7th World Congress in Ultrasound (WFUMB) '94, Sapporo, Japan
Contact: M. Fukuda, Division of Ultrasound, Sapporo Medical College, S-1, W-16, Chuo-ku, Sapporo, Japan

July 24-28, 1994
American Association of Physicists in Medicine (AAPM), 36th Annual Meeting, Anaheim, CA
Contact: AAPM, 335 East 45th St., New York, NY 10017; (212) 661-9404

August 20-26, 1994
World Congress on Medical Physics and Biomedical Engineering: 10th International Congress of Medical Physics and 17th International Conference on Medical and Biomedical Engineering, Rio de Janeiro, Brazil
Contact: Dr. C.G. Orton, International Organization for Medical Physics, Gershenson Radiation Oncology Center, Harper-Grace Hospitals, 3990 John Rd., Detroit, MI 48201

October 11-15, 1994
American Orthotic and Prosthetic Association (AOPA), Annual National Assembly, Washington, DC
Contact: Annette Suriani, AOPA, 1650 King St., Suite 500, Alexandria, VA 22314; (703) 836-7116

November 18-21, 1994
American Speech-Language-Hearing Association (ASHA), Annual Convention, Washington, DC
Contact: Frances Johnston, ASHA, 10801 Rockville Pike, Rockville, MD 20852; (301) 897-5700

November 27-December 2, 1994
Joint Meeting of the American Association of Physicists in Medicine (AAPM) with the Radiological Society of North America (RSNA), Chicago, IL
Contact: AAPM, 335 East 45th St., New York, NY 10017; (212) 661-9404

1995

April 2-7, 1995
International Society for Prosthetics and Orthotics (ISPO), 1995 World Congress, Melbourne, Australia
Contact: ISPO, Australian National Member Society, Repatriation General Hospital, Banksia St., Heidelberg, 3081 Victoria, Australia; Tel (03) 499 6099

AUTHOR AND TITLE INDEX

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NOTE: Principal authors are identified by an asterisk before their name.

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